THE USE OF THE FLUID MAPPER IN AN INVESTIGATION OF FLOW INTO SYMMETRICAL OPENINGS OBSTRUCTED BY PLANE SURFACES

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By

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ACKNOWLEDGEMENTS

At the completion of this work, I should like to express my sincere thanks to Professor Frank A. Thomas, Jr., my council, for this suggestion of the problem and for his continued guidance in the development of this study. To Dr. W. B. Harrison, III, and to Dr. M. J. Goglia, I would express my appreciation for their interest in this study, and for their aid in its completion.

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CHAPTER I

INTRODUCTION TO THE PROBLEM

The opening through which contaminated air flows into an exhaust system is known as a hood. Among the many types of hoods used in industrial applications, the 'canopy hood' is most common. The canopy hood, as the name implies, is that type of hood which is suspended above the source of contamination. This type of hood is particularly suited to the removal of smoke, fumes, and lighter-than-air vapors.

Performance characteristics of the canopy hood are needed for the design of new exhaust installations. Existing literature contains design methods for some simple hood installations. However, the different design equations seldom yield the same solution when applied to a particular hood type, since some of the equations are based on observation of existing installations, some on experiments made with models, and some on extrapolation or combination of the other design methods.

Previous work on the performance characteristics of canopy hoods was done by Thomas (1) in preparation for his masters thesis at the Georgia Institute of Technology. Thomas considered the most general form of hood --- a symmetrical opening obstructed by a plane. Thomas carried out this investigation using the method employed by DallaValle (2) in his study of unobstructed openings. The method consisted of a model and prototype analysis, based on the similarity of velocity contours, in which instantaneous point velocities were measured with a modified Pitot tube and a differential micro-manometer.

It is the purpose of this investigation to utilize an analogy method, based on the fluid mapper technique, to determine the flow characteristics of plane obstructed openings.

This analog employs two-dimensional, incompressible flow to simulate the centerline-plane characteristics of three-dimensional flow. In any analogy the results obtained may vary to a degree from those of the actual installation. With the selection of a proper analog this deviation will be small. The simplicity of investigating an analog tends to outweigh the advantages of the additional accuracy obtained by carrying out a full scale experiment on the prototype.

The fluid mapper appears to provide a simple method for investigating hood performance. The method is particularly desirable in that complicated instrumentation is not required for the study. The fluid mapper is inexpensive to construct and is simple to operate. For these reasons, it is feasible to investigate more variables affecting hood performance with the mapper than would be possible with other methods.

CHAPTER II

TEST EQUIPMENT AND OPERATION

Test Equipment.--The fluid mapper employed was essentially patterned after those constructed by Moore (3). The mapper consists of a laminar flow space bounded by a plaster slab and a piece of plate glass, separated from the slab by appropriate spacers or baffles. Sources and sinks to operate the mapper are provided by openings in the plaster slab which are connected to leveling bottles. The entire slab and glass assembly is submerged in a shallow pan of water during operation. Crystals of potassium permanganate, placed within the laminar flow space, are used to make the pattern of flow visible. This pattern is recorded by photographic methods for later study.

The basic mapper for the canopy hood analog consisted of an eight and one-half inch by twelve inch slab cast of artificial stone; a sixty degree exhaust hood silhouette cut from Plexiglas; a thirteen inch strip of the same material to represent the plane obstruction; a nine and one-half inch by sixteen inch cake pan; and a piece of plate glass slightly smaller than the slab.

The Plexiglas hood contained the sink, which represented the means of suction. This hood was fastened to the slab with water-proof cement. The plane obstruction was located a given distance away from the hood and held in place temporarily. The slab assembly was then placed in the cake pan and leveled with a spirit level. Approximately three inches of water were poured into the pan, care being taken not to disturb the leveled slab.

After the slab was covered with water the leveling bottle was raised and lowered several times to remove any air in the sink and connecting lines. When all the air was removed, the plate glass was lowered into the water and placed on the hood and plane silhouette. This formed a one-sixteenth inch flow space between the slab and the glass. Any air trapped in the flow space was removed with a small suction hose. Crystals of potassium permanganate, which previously had been screened to approximately one-sixteenth inch size, were then placed upon the slab and gently pushed beneath the plate glass with a stiff wire. The mapper was then ready for operation.

Operation of the Mapper.—In operation the leveling bottle was lowered several inches, causing the fluid to flow into the sink. The crystals of potassium permanganate formed the heads of colored streamlines which clearly outlined the flow pattern in the vicinity of the hood.

Additional Equipment.—The photographic equipment used consisted of a 35 millimeter camera mounted on an adjustable stand directly above the fluid mapper. Lighting was provided by two photoflood lamps mounted adjacent to the camera. The apparatus for reproducing the photographs taken of the mapper in operation consisted of a 35 millimeter slide projector and a copying stand.

A modification of the basic slab was used for the third series of experiments. This slab was cast three inches longer than the basic slab and had a vertical slot one and one-half inches in from each of the short sides. When one of these slots was operated as a source and the other as a sink, the effect of a uniform current across the hood face was created.

A photograph of the experimental set up for the third series of experiments is shown in Figure 1.

Figure I. Arrangement of Experimental Apparatus

CHAPTER III

TEST PROCEDURE

Three series of plane obstructed openings were studied in this investigation. A sixty degree exhaust hood silhouette was used in all three series. The hood was obstructed by a plane the width of which was equal to that of the hood for the first series of experiments. The plane obstruction simulated an infinite width for the second series. For the third series of experiments, the effects of a uniform current across the face of the hood obstructed by the "infinite" plane were studied.

A unit system was selected for describing the geometry of the hood and obstruction. The basic unit was the width of the hood at the opening. The plane obstruction was placed parallel to the hood face in eight different locations for each of the three series of experiments. The first position was 1.75 units away from the hood face. The obstruction was then moved towards the hood in increments of 0.25 units until a position 0.25 units away from the hood was reached. The final location of the plane was 0.10 unit away from the hood.

The region studied for the first series consisted of the area bounded by the centerline of the hood and a parallel line 1.50 units from the centerline. The upper and lower boundaries were lines 0.25 units above the face of the hood and 0.25 units below the plane obstruction. For the second and third series of experiments the lower boundary was the plane surface.

The first and second series of experiments were set up and run as described in Chapter II. For the final series a slab, modified to provide a cross current, was used. The leveling bottle, which served as the source of the cross current, was filled with green dye. A colored front resulted so that the effect of the cross current could be observed. The cross current was operated with a lower differential head than the hood so that the hood effect would be more pronounced. Figure 2 is a photograph of the modified slab in operation.

After the photographic film was processed the negatives were placed in a slide projector and a tracing or 'map' of the flow pattern was made. The flow lines were made by tracing the outlines of the colored stream tubes on rectangular coordinate paper. These lines formed the streamlines of the completed map. Isopotential lines were then constructed orthogonal to the streamlines in the field of study. The map was completed by locating the lines of constant velocity. The positions of these lines were found by arbitrarily selecting a line within the hood as a line of constant velocity and then applying the equation of continuity to locate other constant velocity lines.

When this phase of the work was complete the map was ready for analysis.

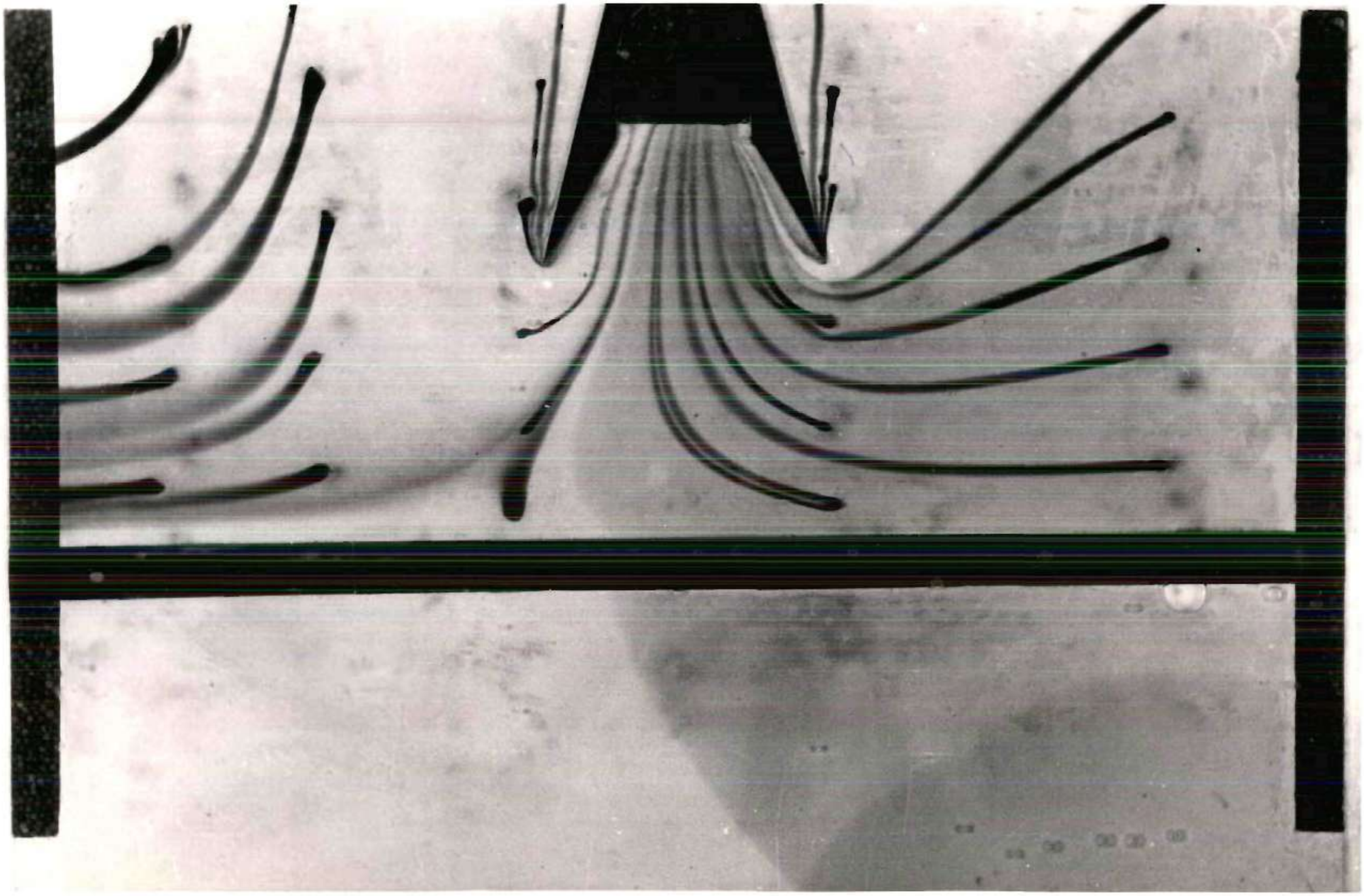

Figure 2. The Fluid Mapper in Operation

CHAPTER IV

DISCUSSION OF RESULTS

The fluid mapper used in the preceeding experiments was necessarily limited to one particular type of symmetrical opening. This opening was a rectangular hood of infinite length, or, for more practical consideration, a hood of a relatively high length to width ratio, or one in which end effects are negligible. The mapper should also give acceptable results for exhaust openings consisting of very narrow slots.

The completed map of the flow field gives a pictorial representation of the hood characteristics. The streamlines show the path that the contaminated air must follow in order to enter the hood. The iso-potential lines, drawn orthogonal to the streamlines, are lines of constant pressure as was shown by Prandtl (4) (see Appendix 2). The most important hood characteristic shown is the series of constant velocity lines. The velocity, as a criterion of hood performance, shows the ability of the hood to 'reach out' and capture the contaminated air. The velocity curves are represented as percentage of the reference velocity at the centerline of the hood face.

The control point selected for a detailed study is on the surface of the plane obstruction and 0.50 unit from the centerline of the hood. This point represents the outer boundary of the contaminant which is expected to enter the hood.

Obstruction of Unit Width.—An examination of the streamlines in the first series of experiments (Appendix 3, Figures 9-16) shows that the flow over the obstruction conforms to the geometry of the obstruction. The lower bounding streamline enters along the centerline of the hood, regardless of the location of the plane. Any contaminant on the plane surface will therefore enter the hood provided the velocity at the plane is sufficient. The lines of constant velocity diverge rapidly, so that in extreme locations of the obstruction the percentage velocity is very low. As the obstruction is moved towards the hood, the locations of the lines of high constant velocity are further removed from the hood ––– that is, the effective range of the hood is extended. At some point between 0.75 units and 0.50 units for the plane location, the velocity distribution changes rapidly until all points beneath the hood are 65 to 70 per cent of the reference hood velocity. The velocity characteristics of the control point are shown graphically in Figure 3. This curve when plotted on logarithmic coordinates can be rectified to yield the equation

$$V_p = V_c \left[0.53\, D^{-0.884} - 0.35 \right] \qquad (1)$$

where V_p is the control point velocity, V_c is the centerline velocity and D is the number of units the obstruction is removed from the hood. This equation expresses the control point velocity as a function of the plane location.

As the plane is moved towards the hood the more remote velocity contours tend to coincide with the isopotential lines.

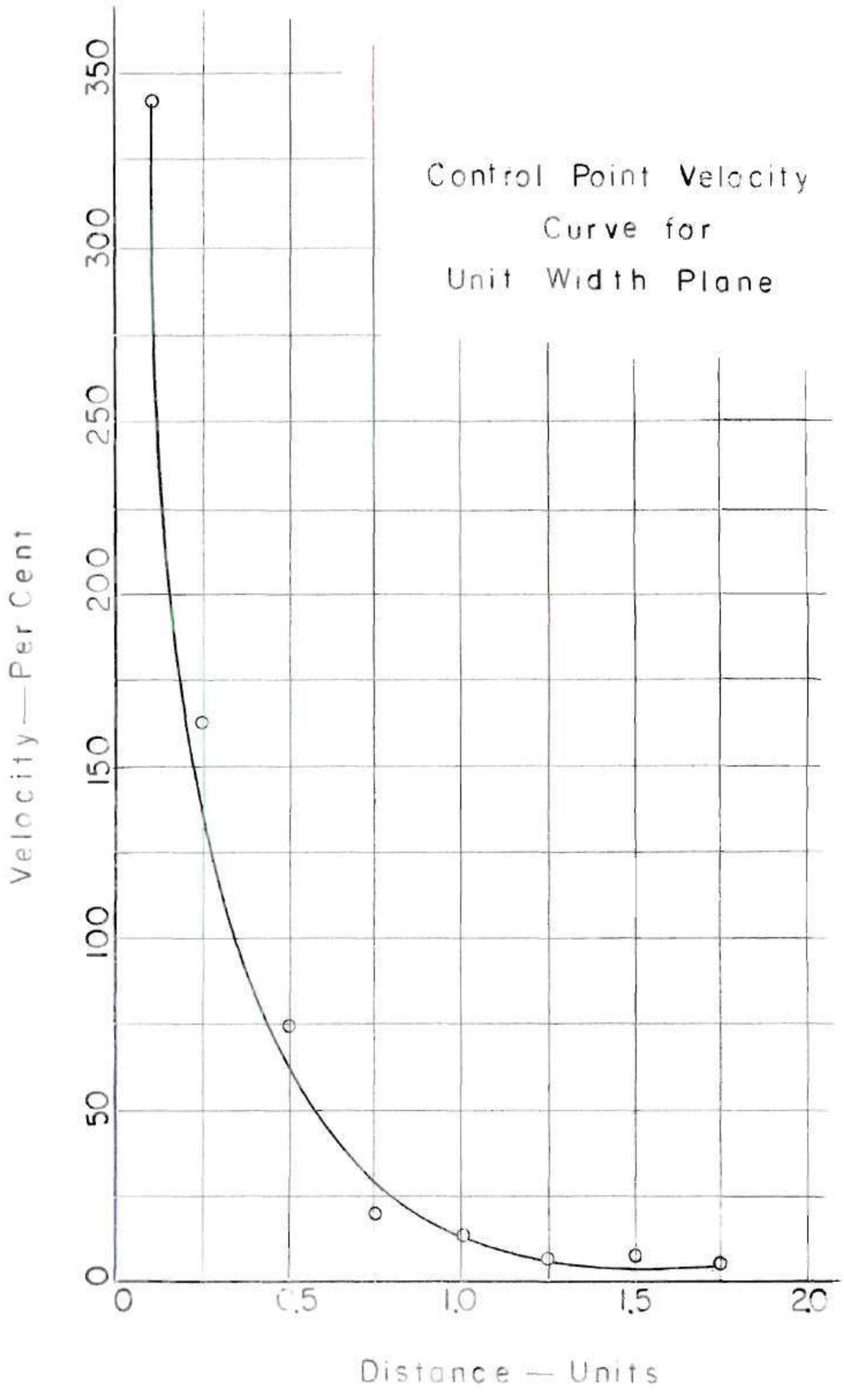

Figure 3. Velocity vs. Distance, Series I.

Obstruction of Infinite Width.---Appendix 3, Figures 17-24, shows the completed maps for the infinite plane obstruction. The lower bounding streamlines for this case also follow the plane boundaries and enter the centerline of the hood. The velocity contours for the infinite plane are very similar to those of the short plane in the region studied. Although higher relative velocities might be expected in the case of the infinite obstruction, Figure 4 shows the per cent velocities at the control point to have the same order of magnitude as in the case of the plane of unit width. The equation for velocities at the control point was found to be

$$V_p = V_c \left[0.65 \bar{D}^{0.810} - 0.40 \right] \tag{2}$$

where the symbols have the same meaning as in the previous equation. As before, the velocity contours and isopotential lines tend to coincide for the lower velocities.

Obstruction of Infinite Width with Cross Current.--The effects of a uniform cross current are shown in Appendix 3, Figures 25-32. The average velocity of the draft was 25 to 35 per cent of the reference hood velocity for all eight runs. The dashed lines on these maps indicate the bounding streamlines of hood influence as determined by the colored dye front. An examination of the maps for the first four runs, Figures 25-28 shows the field divided into four areas by the bounding streamlines. The stagnation point (S) — a point of zero velocity -- is indicated in the figures. The stagnation point seems to be located in approximately the same position regardless of the plane location. The first three maps of the cross

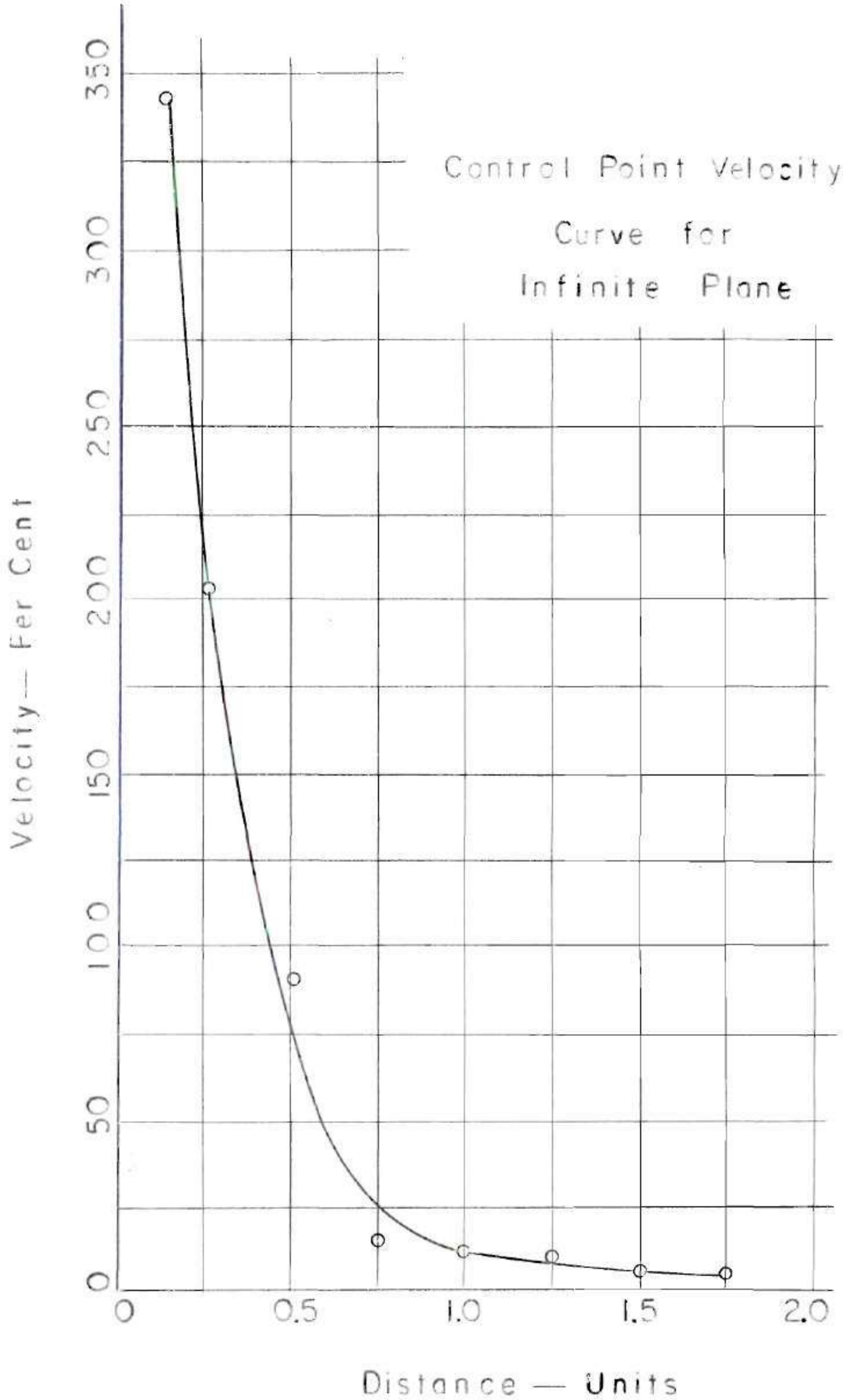

Figure 4. Velocity vs. Distance, Series 2

current show that the hood is completely ineffective since all contamination is swept away from the hood by the cross draft. The fourth map indicates that while a great portion of the field is influenced by the draft, the critical portion directly beneath the hood lies in the zone of hood influence.

The remaining figures show that although the draft still tends to sweep the contamination away, the hood velocity is sufficient in all cases to capture the contaminated air. The draft actually assists in the capture on the source side of the hood by moving the contamination towards the center of the hood. A further examination of the maps shows that the percentage velocity lines on the source side of the hood are more removed from the centerline than lines of the same magnitude on the sink side. Figures 29-32 show the location of the stagnation points on the surface of the plane. The control point in the case of a cross draft lies under the hood boundary on the sink side of the hood. The cross draft at this point is working against the influence of the hood. The velocity curve for this point is shown in Figure 5. This velocity distribution is expressed as

$$V_p = 0.33\, V_c\, D^{-1.04} \tag{3}$$

This equation is valid only in the range between D = 1.00 units and D = 0.10 units.

As in previous cases velocity and pressure lines almost coincide for the lower velocities.

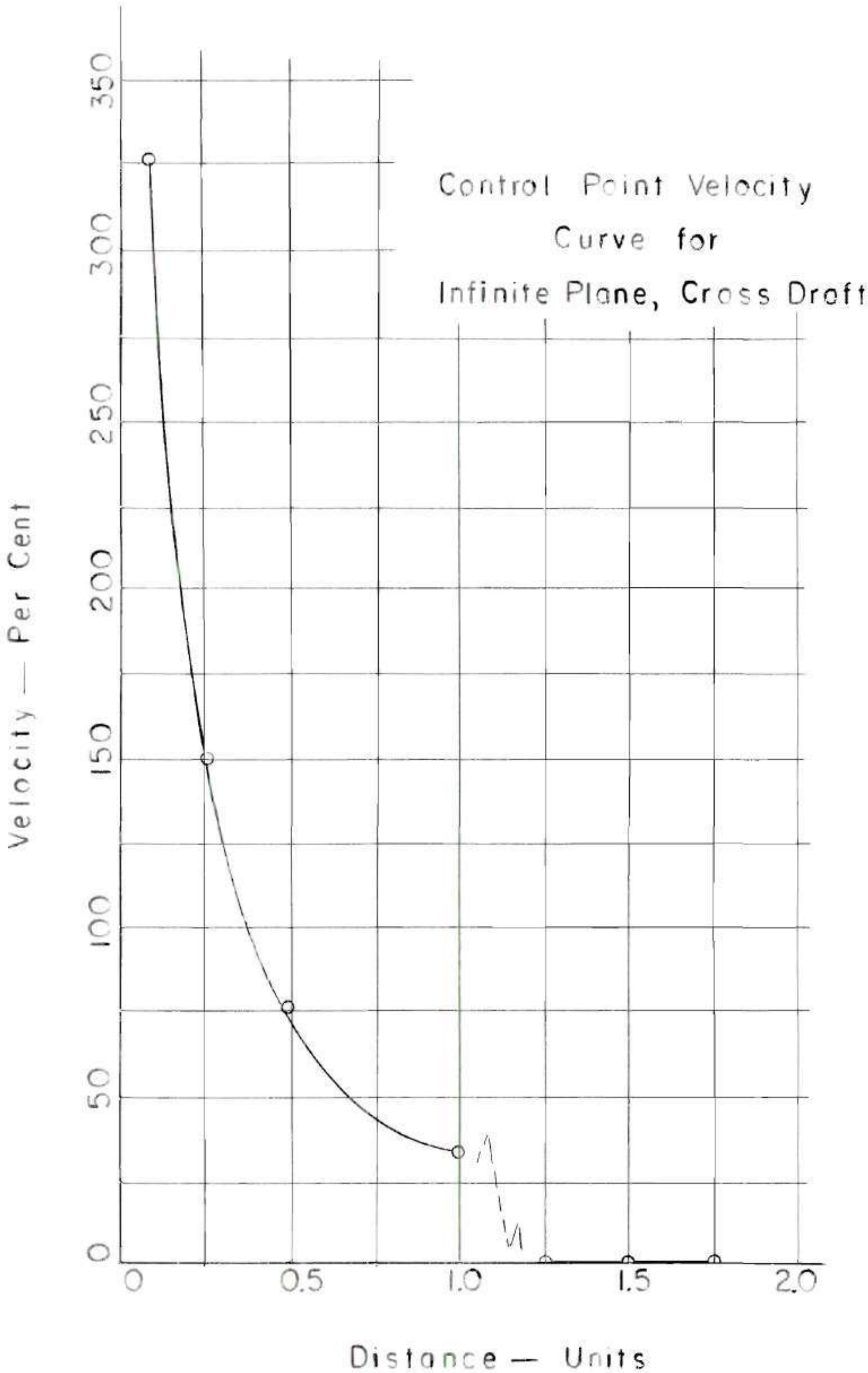

Figure 5. Velocity vs. Distance, Series 3

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions.--The object of this study was to investigate flow into canopy type exhaust hoods by using a fluid mapper analog. The fluid mapper as constructed was limited to rectangular openings of large length-to-width ratio. The mapper enabled a plot of hood characteristics, including streamlines, pressure lines and velocity lines to be constructed with a minimum of experimental apparatus and equipment. Although no data were available for checking the results of this type hood and obstruction arrangement, it is felt that the method gives sufficient representation of the flow characteristics to aid in exhaust hood design.

Recommendations.--It is recommended that further work be carried out in adapting the fluid mapper to exhaust hood problems. By using the method suggested by Moore (5) for studying three-dimensional fields having an axis of symmetry, a study of circular hoods and an approximation of the characteristics of square hoods could be made. The effects of a uniform draft across an infinite hood obstructed by a plane of unit width should also be investigated.

A more complete investigation of the characteristics of any of the above hoods could be made by introducing a point source at the control point to simulate a source of contamination at this point.

APPENDIX 1

CONSTRUCTION OF A TWO DIMENSIONAL FLUID MAPPER

The basic component of the fluid mapper is the plaster slab. This slab forms the lower boundary of the flow space, so it must be smooth and uniformly flat in order that the flow be equal. The slabs used in this series of experiments were cast of an artifical stone, know commercially as 'Lab-stone'. This plaster has desirable properties for mapper work: it expands slightly after rapid setting, is durable, and is relatively unaffected by immersion in water.

The first step in mapper construction was laying out the full scale slab design on paper, showing the location of all sources and sinks. A piece of plate glass was then placed over the drawing to form the bottom of a mold, which held the liquid plaster. The mold was completed by constructing a dam of the desired slab size on the glass. The author used four piece of steel bar stock, approximately two inches square, to form this dam. The stock was heavy enough to stay in place without anchoring and formed an almost watertight seal with the glass. Cores for the larger openings in the slab were made from various pieces of scrap metal. These cores were held in place during pouring with household cement. The mixture for the slabs was in the proportions of five parts powder to two parts water, the powder being added to the water during mixing. The mixture was allowed to set approximately ten minutes after being poured into the mold. After this initial set the entire assembly was immersed in water and the cores and mold edges were removed.

Plenum chambers for the sources and sinks were made from galvanized sheet metal. The metal was bent to shape and the joints soldered. One-eighth inch copper tubing was soldered through the walls of the chambers to form connections for the hoses. Copper screen was next fastened under the openings in the slab. The plenum chambers were then anchored in place over the screen with additional Lab-stone.

The openings were filled with copper and lead shot. The larger shot was placed next to the screen and the openings were filled flush with the surface of the slab with the smaller shot. This shot bed insured a uniform flow.

Barriers for the mapper were made from one-sixteenth inch Plexiglas. The outline of the barrier was etched onto the Plexiglas with a scratch-awl. This outline was cut from the Plexiglas with a band or jig saw. The edges of the barrier were then filed to exact size and sanded smooth. It was found advisable to darken the Plexiglas with india ink in order that the barriers be distinguishable in the photographs.

An ordinary cake pan was used for the mapper. The inside of the pan was first painted to prevent rusting. One-eighth inch copper tubing was soldered through the sides of the pan at appropriate locations to provide connections for the leveling bottle hoses.

Leveling bottles of the laboratory type with hose connections near the bottom were found satisfactory for the mapper work.

A piece of plate glass cut slightly smaller than the slab and several lengths of thin walled rubber tubing completed the necessary mapper equipment.

APPENDIX 2

MEANING OF STREAM FUNCTION FOR FLOW BETWEEN PLATES

For fluids flowing between flat plates, as in a fluid mapper, Prandtl (6) gives the following explanation of the stream function:

> When the velocities are sufficiently small, however, the mean value of the velocity over the gap between the plates may again be taken as proportional to the fall of pressure, i.e., we have
>
> $$u = -k\frac{\partial p}{\partial x} \quad ; \quad v = -k\frac{\partial p}{\partial y} \qquad (30a)$$
>
> for the velocity components. Hence from the equation of continuity
>
> $$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$
>
> gives
>
> $$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = 0 \qquad (31a)$$
>
> again in analogy with the velocity potential for the flow of frictionless fluid in two dimensions.

In the above derivation the symbols have the following meanings:

u = velocity component in the x direction

v = velocity component in the y direction

k = a constant of proportionality

p = pressure

Thus we see that in the fluid mapper analog the isopotential lines are lines of constant pressure.

APPENDIX 3

DEVELOPMENT OF EQUATIONS

The velocity distribution curves for the control point in the first and second series of runs can be rectified into a straight line when plotted on logarithmic coordinate paper. The general form of these rectified curves on logarithmic paper is

$$Y = A X^{m} - C \tag{3.1}$$

where Y = function plotted on ordinate

X = function plotted on abcissa

m = slope of line

A & C = constants

Unit Obstruction.—From Figure 6 we find that the equation of the control point velocity is

$$Y = 53 X^{-0.884} - 35 \tag{3.2}$$

A more useful form of the equation is obtained if the functions are substituted into the equations. The function on the Y axis is the per cent centerline hood velocity, or the control point velocity divided by the centerline velocity:

$$Y = \frac{V_p}{V_c} \times 100 \tag{3.3}$$

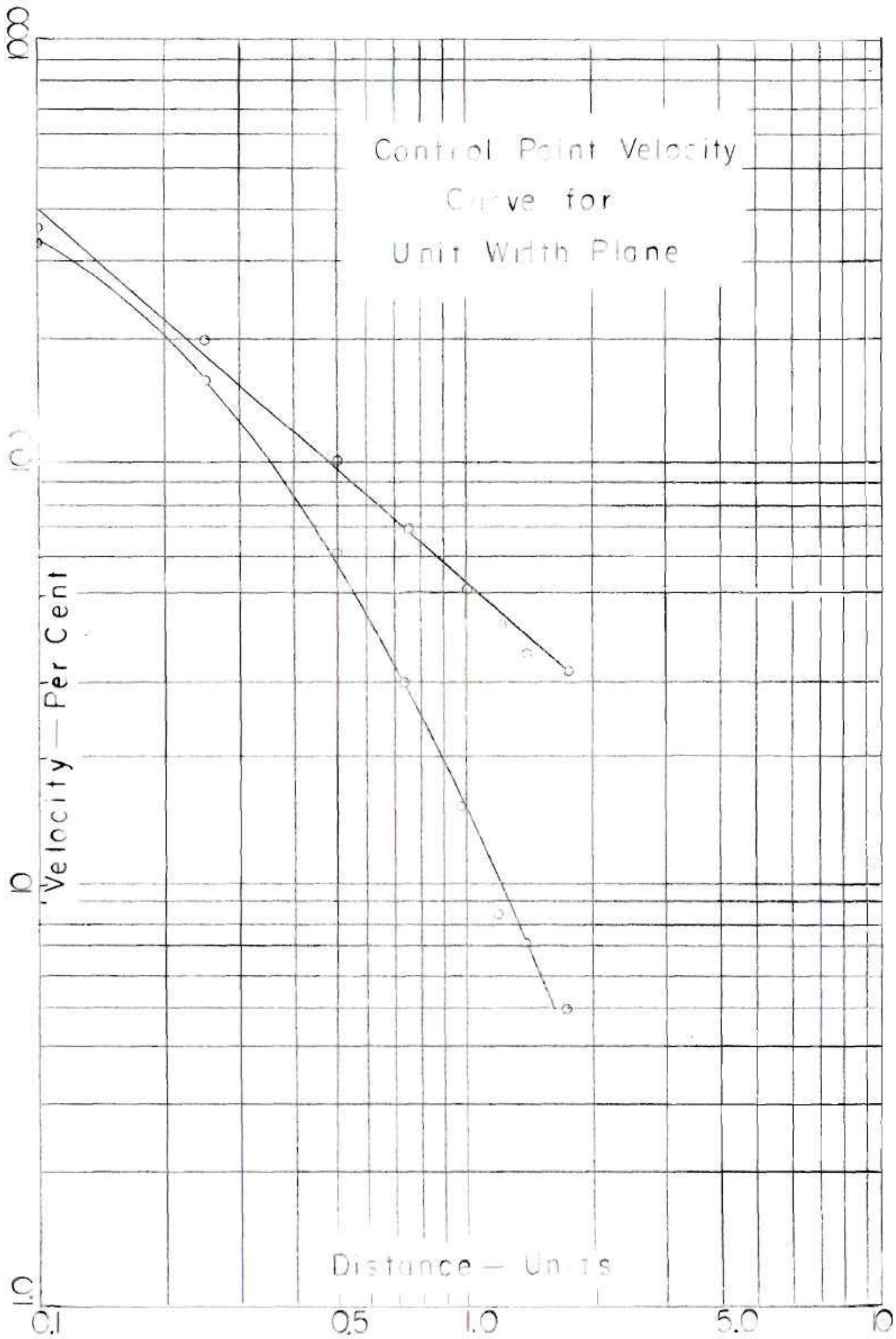

Figure 6. Velocity vs. Distance, Series I.

The X axis is the distance the plane is removed from the hood expressed in units of hood width. The equation now becomes

$$\frac{V_p}{V_c} \times 100 = 53\,D^{-0.884} - 35 \tag{3.4}$$

Solving for the control point velocity

$$V_p = V_c \left[0.53\,D^{-0.884} - 0.35 \right] \tag{1}$$

Infinite Plane Obstruction.--A similar analysis of Figure 4, the infinite plane curve, yields

$$V_p = V_c \left[0.65\,D^{-0.810} - 0.40 \right] \tag{2}$$

where the symbols used are the same as for the unit obstruction. The logarithmic plot of Figure 4 is shown in Figure 7.

Infinite Plane with Cross Current.--The portion of Figure 5 which was in the range of hood influence is plotted on logarithmic paper in Figure 9. The general equation of this curve is

$$Y = A\,X^{m} \tag{3.5}$$

where the symbols have the same meaning as in equation 3.1. From Figure 8 we find the equation of the curve to be

$$Y = 33\,X^{-1.04} \tag{3.6}$$

Substituting for the functions used and solving for V_p we obtain

$$V_p = 0.33\,V_c\,D^{-1.04} \tag{3}$$

This equation is only valid for values of D between 1.00 units and 0.10 units.

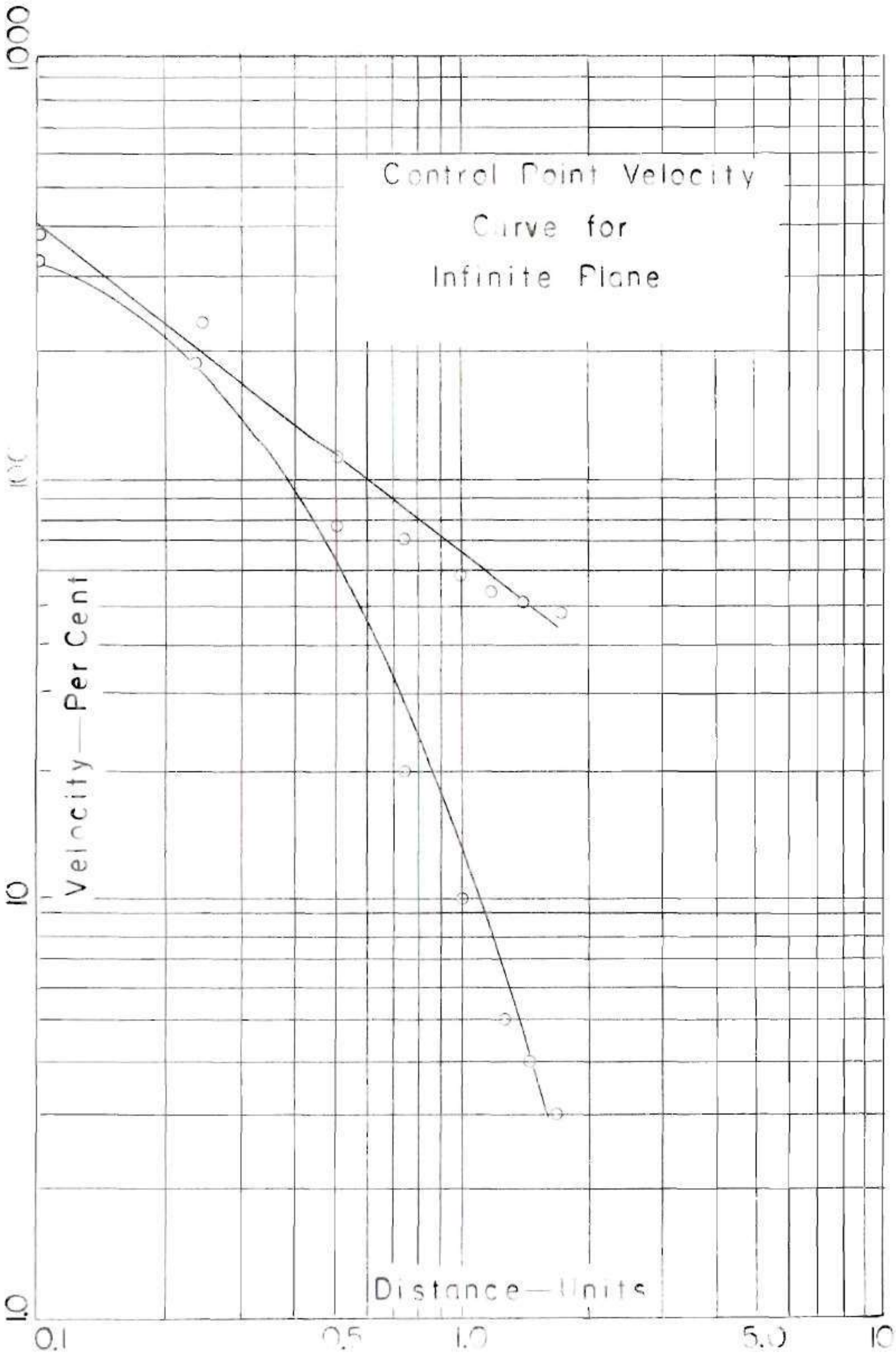

Figure 7. Velocity vs. Distance, Series 2

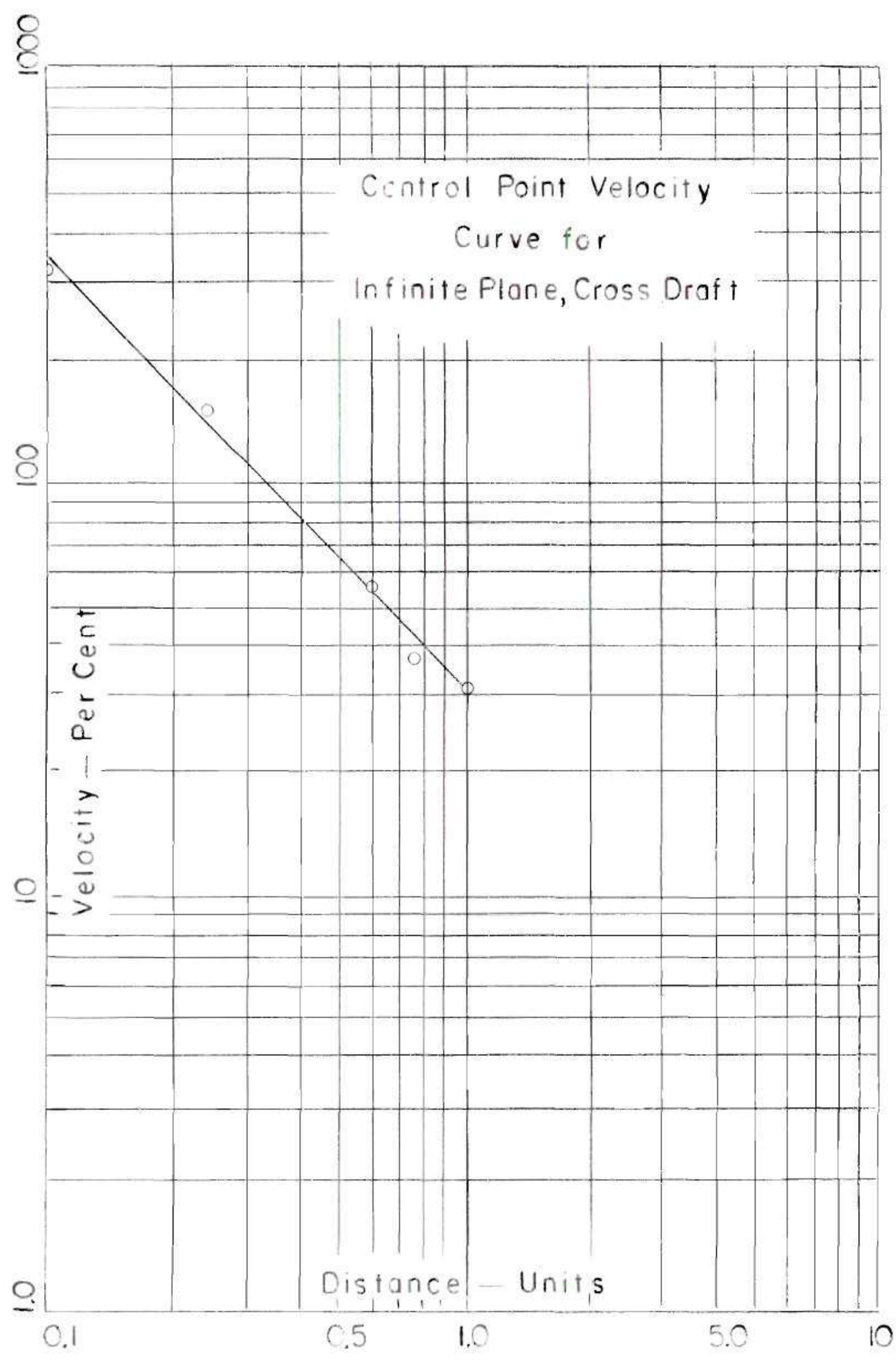

Figure 8. Velocity vs. Distance, Series 3

APPENDIX 4

MAPS OF FLOW FIELDS

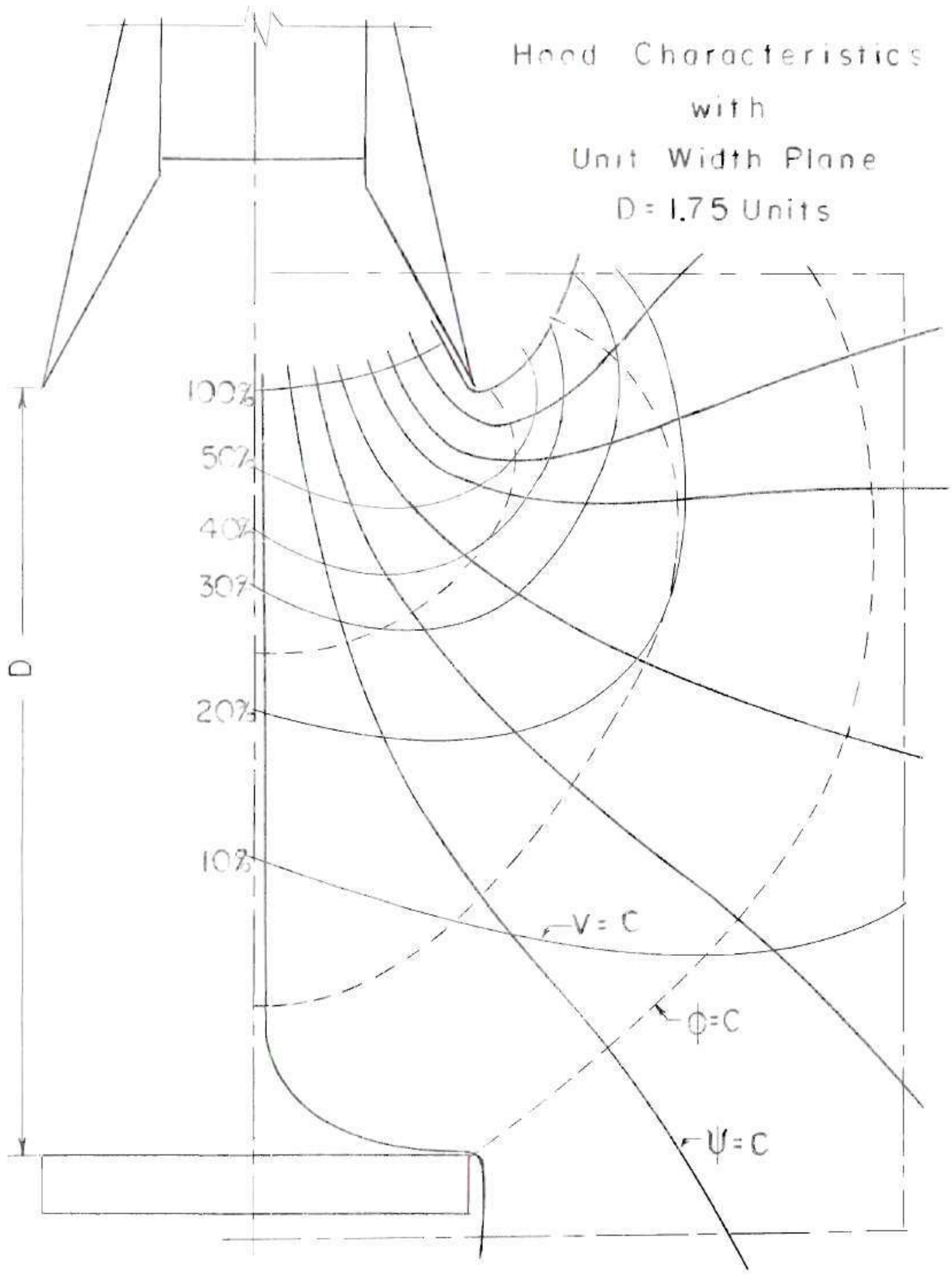

Figure 9. Map of Flow, Series Ia.

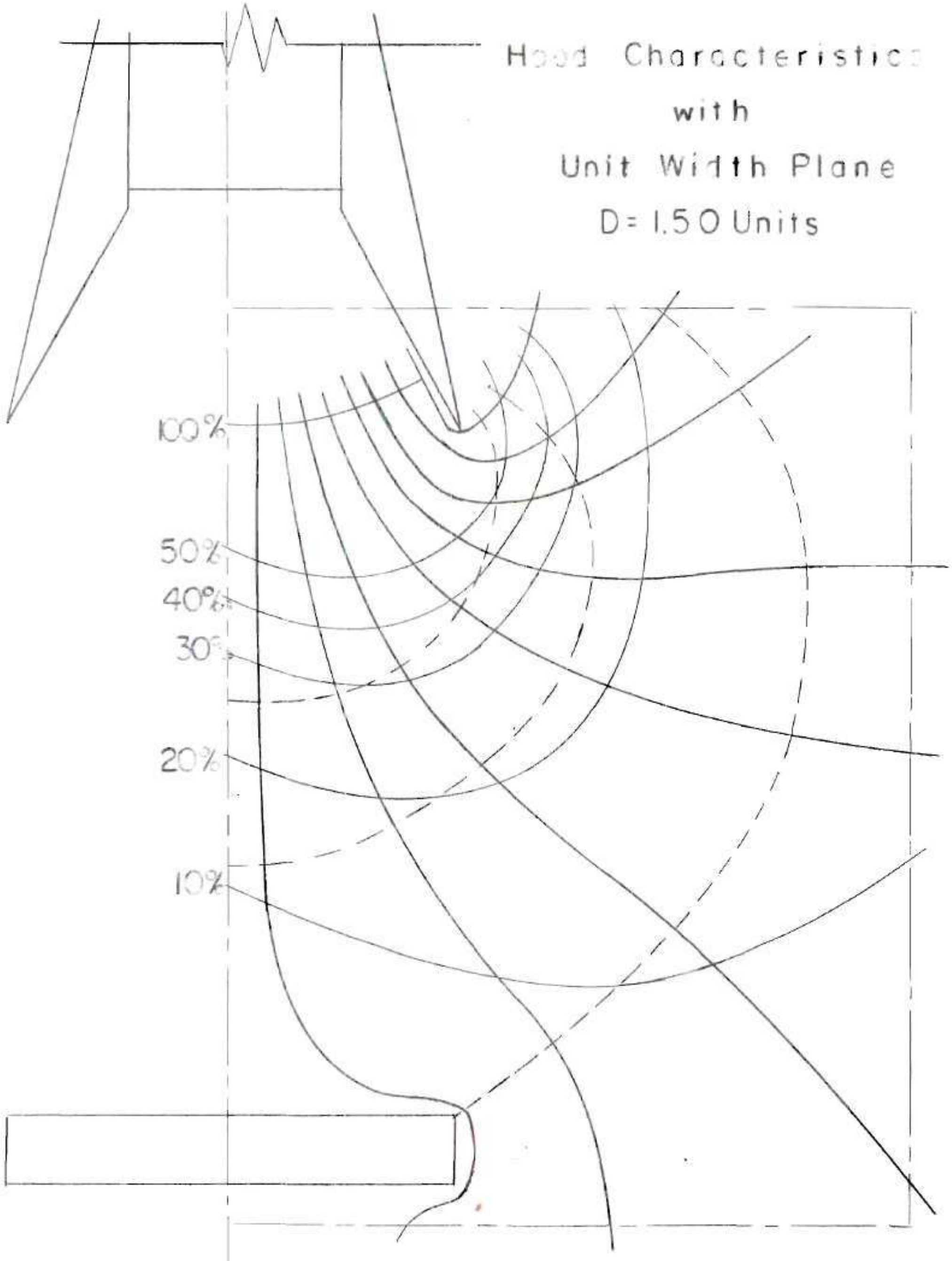

Figure 10. Map of Flow, Series Ib

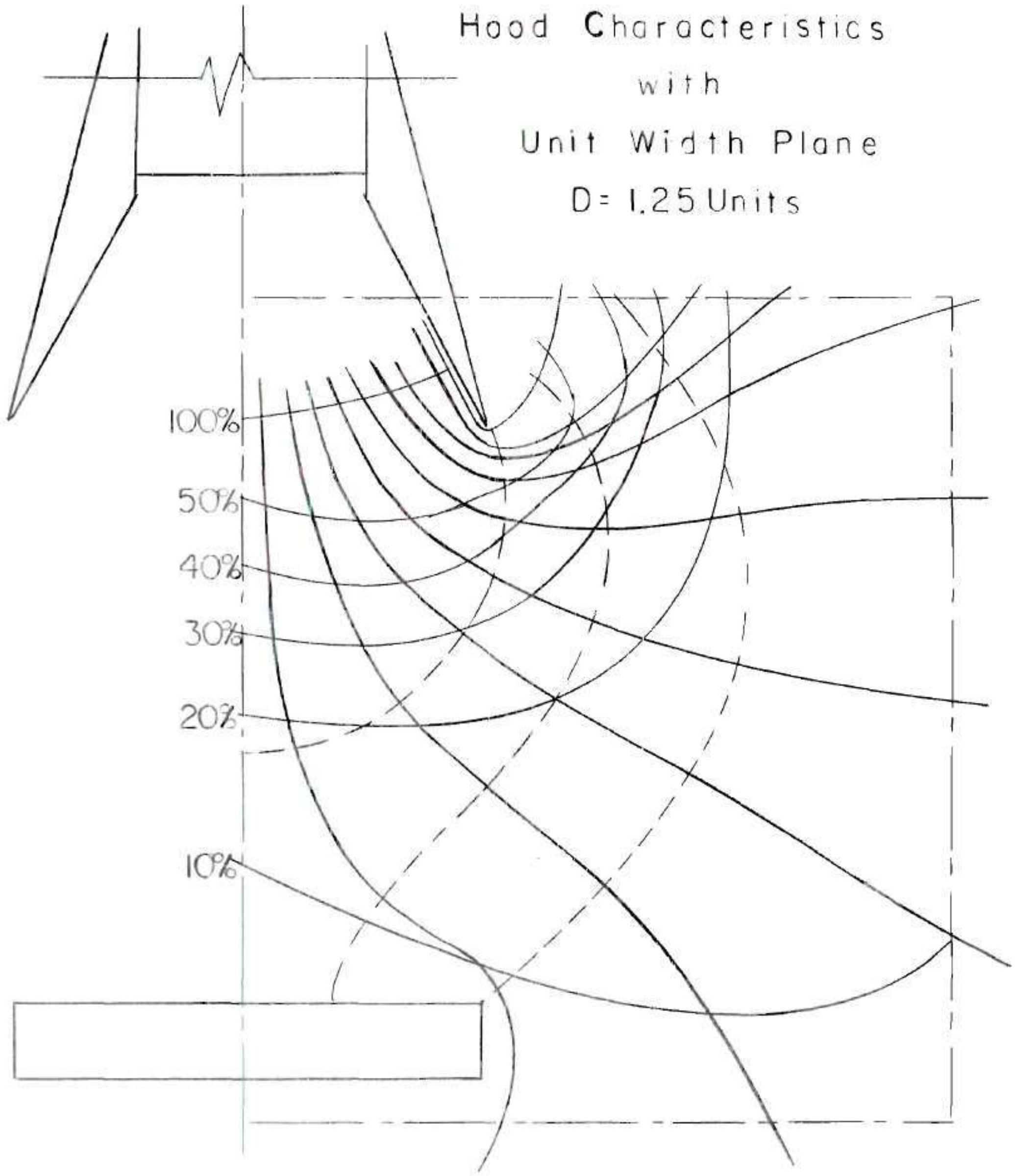

Figure 11. Map of Flow, Series Ic

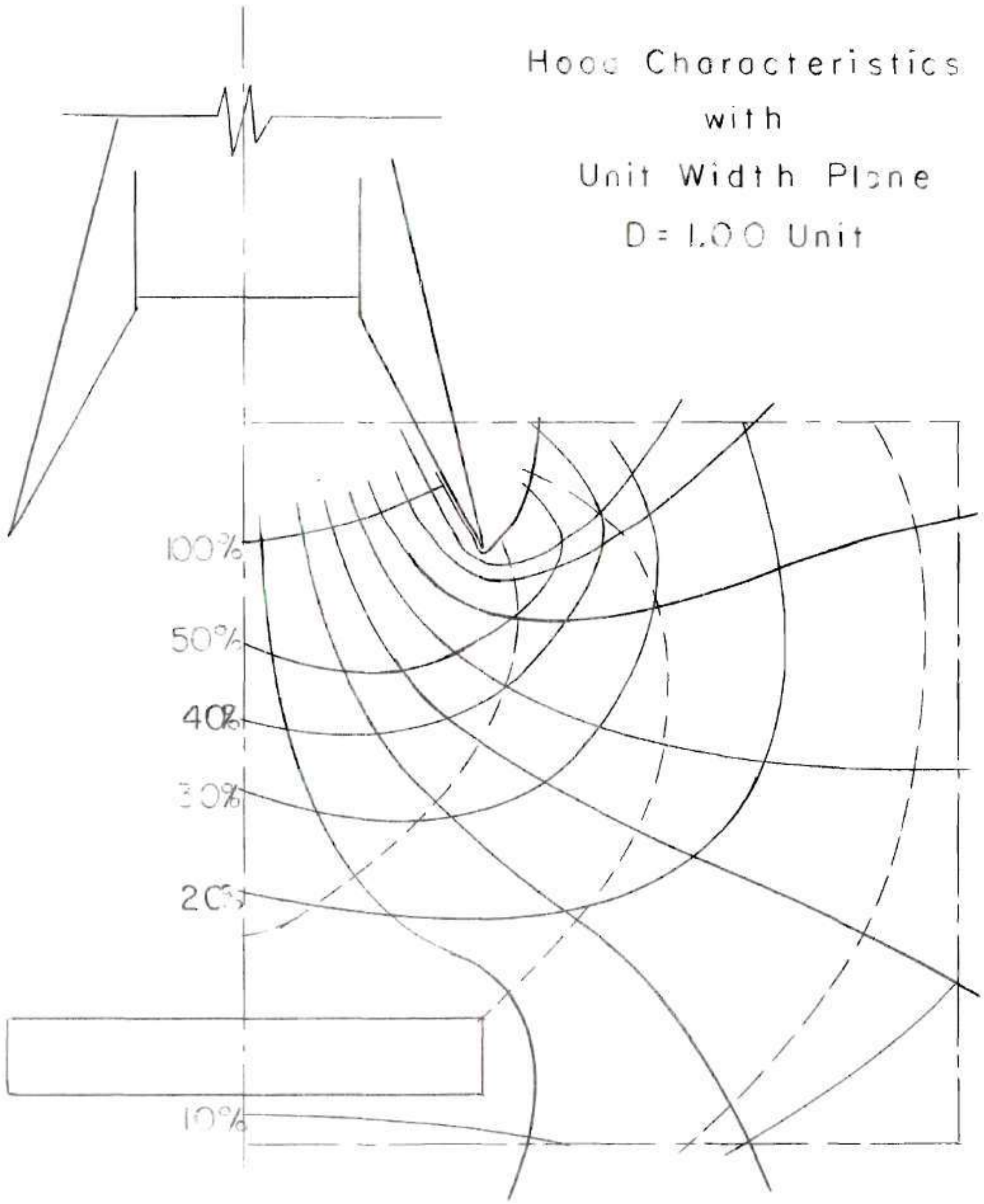

Figure 12. Map of Flow, Series Id

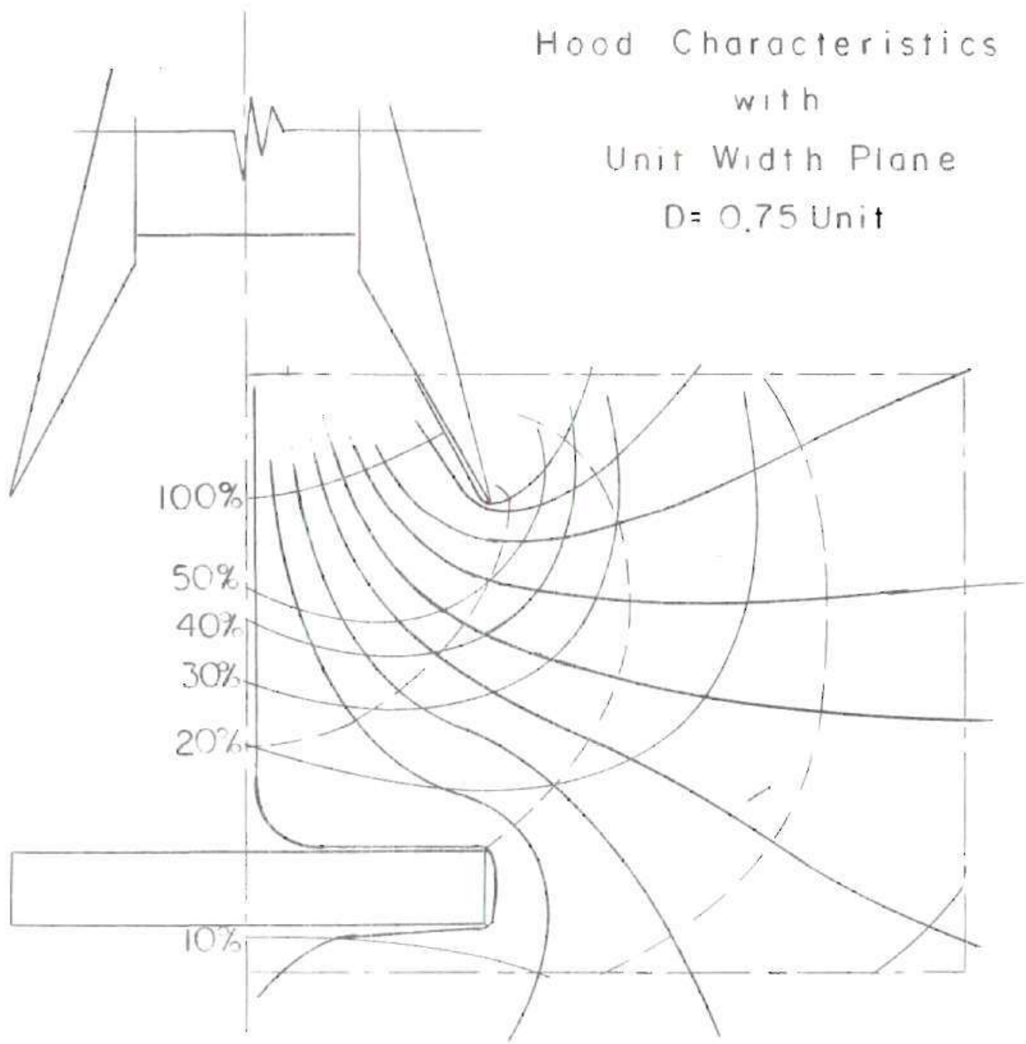

Figure 13. Map of Flow, Series Ie

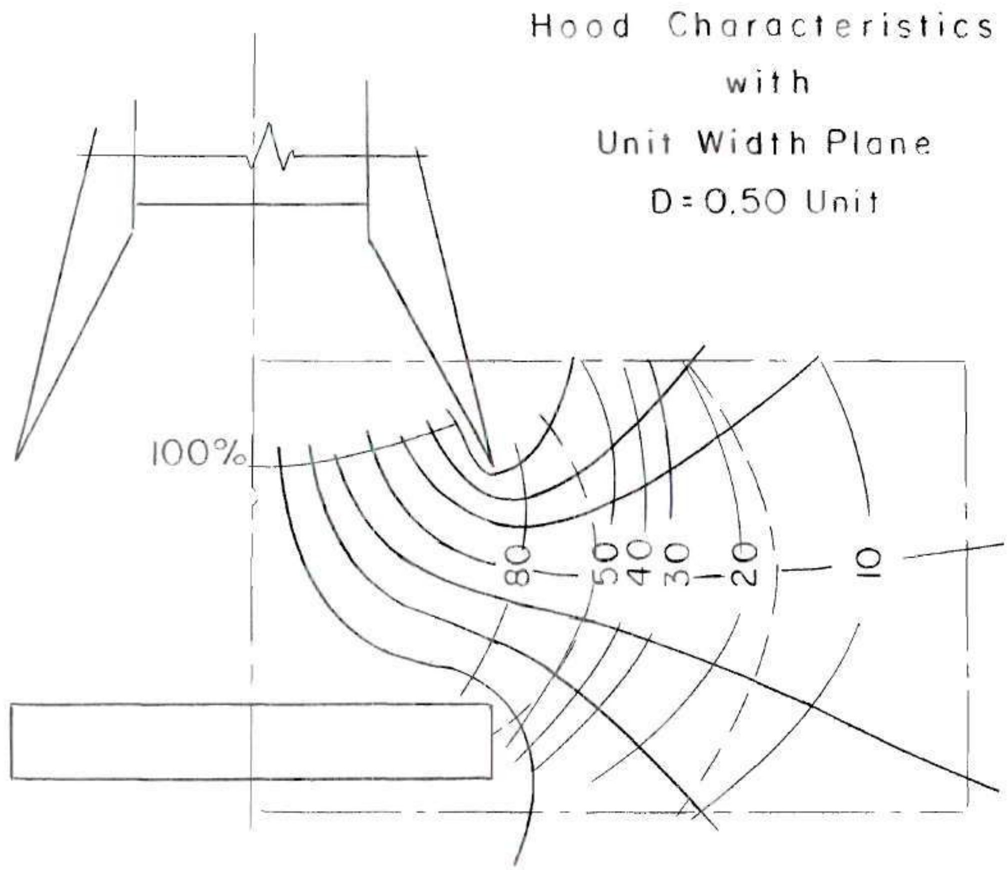

Figure 14. Map of Flow, Series If

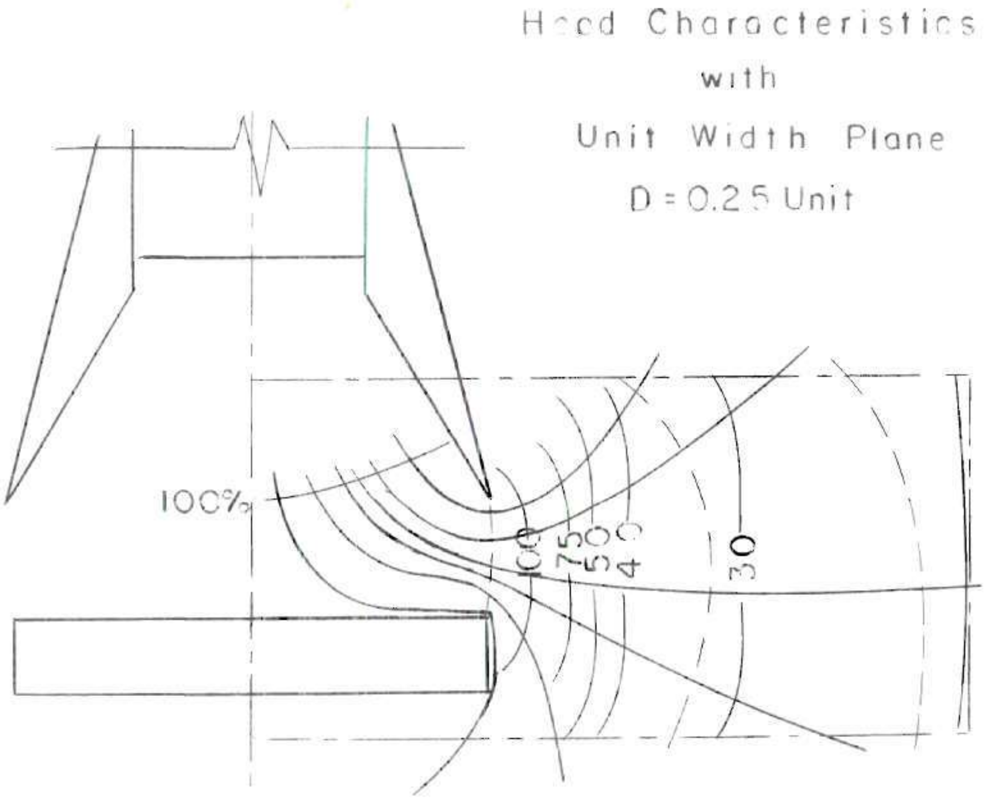

Figure 15. Map of Flow, Series Ig

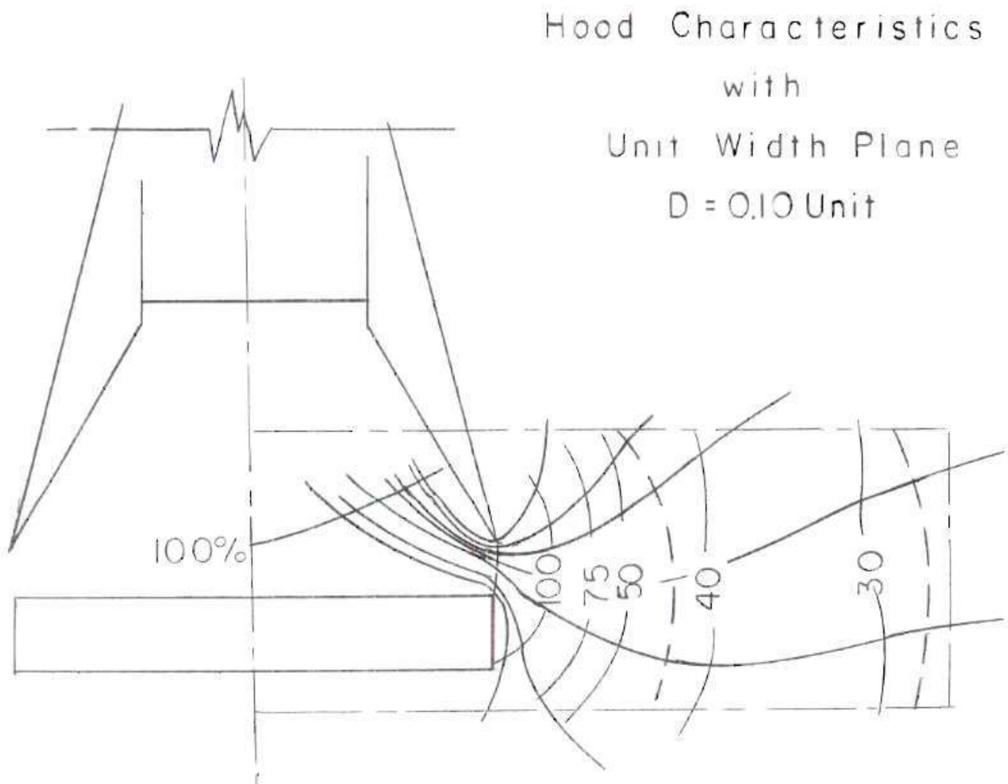

Figure 16. Map of Flow, Series Ih

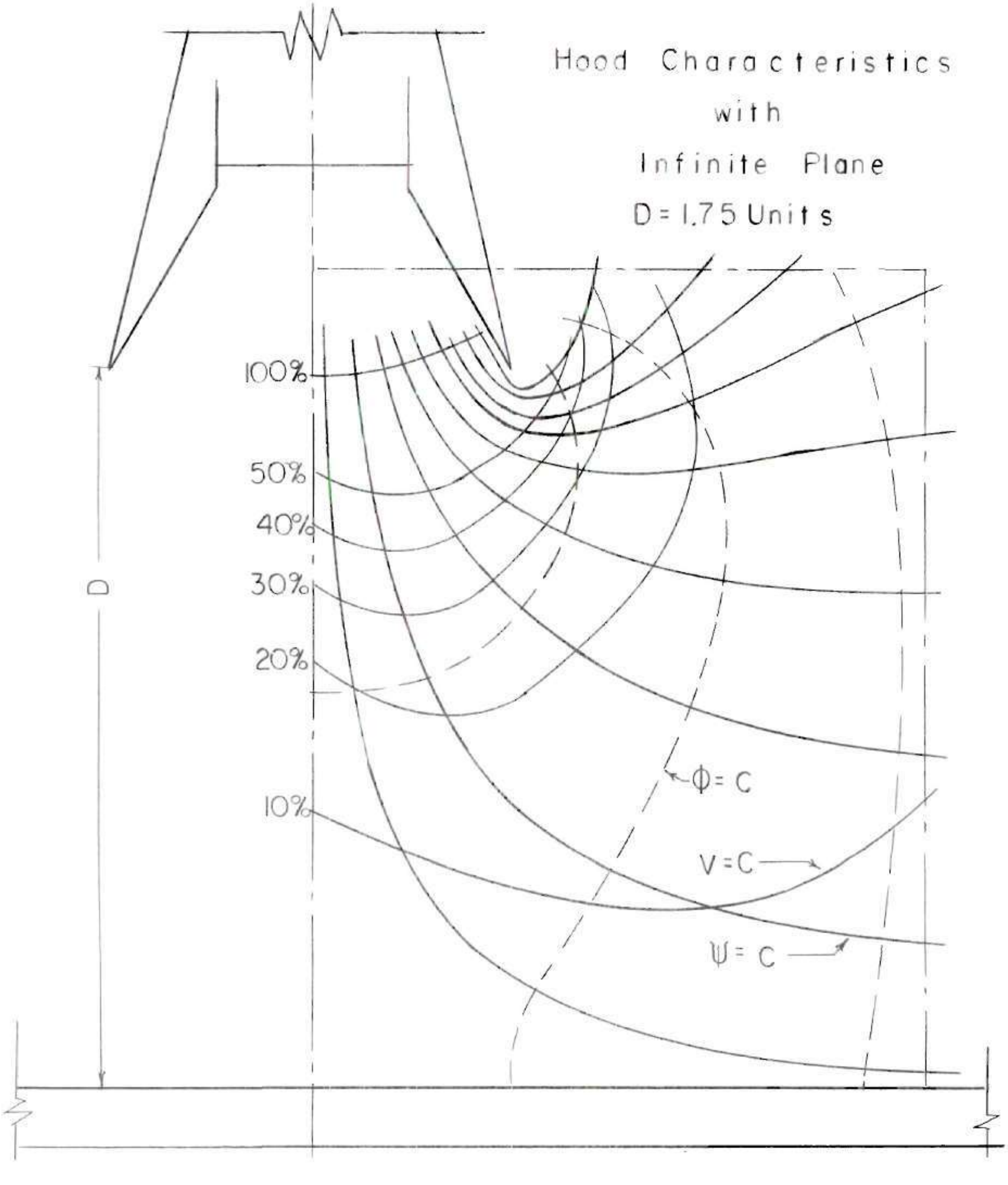

Figure 17. Map of Flow, Series 2a

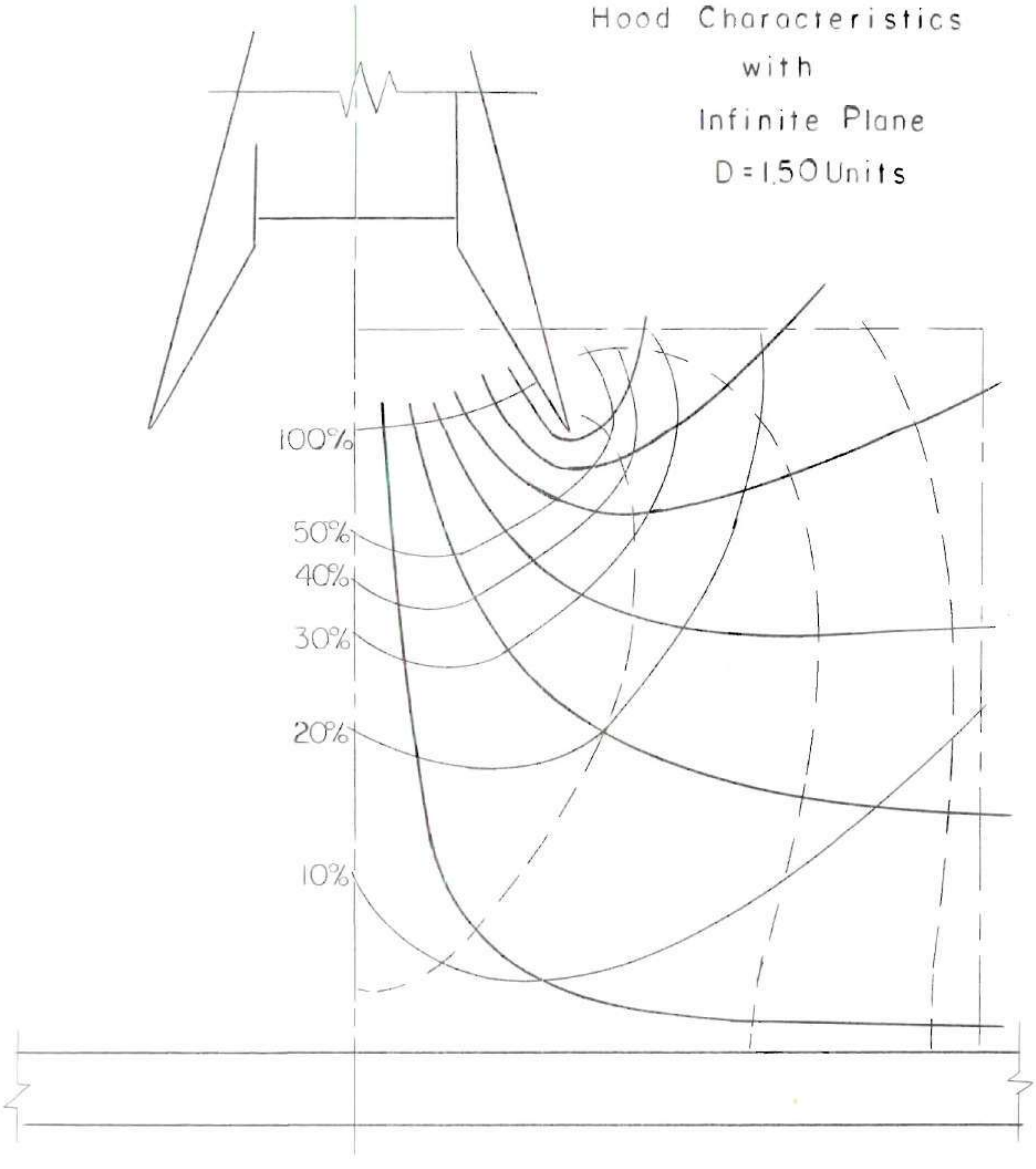

Figure 18. Map of Flow, Series 2b

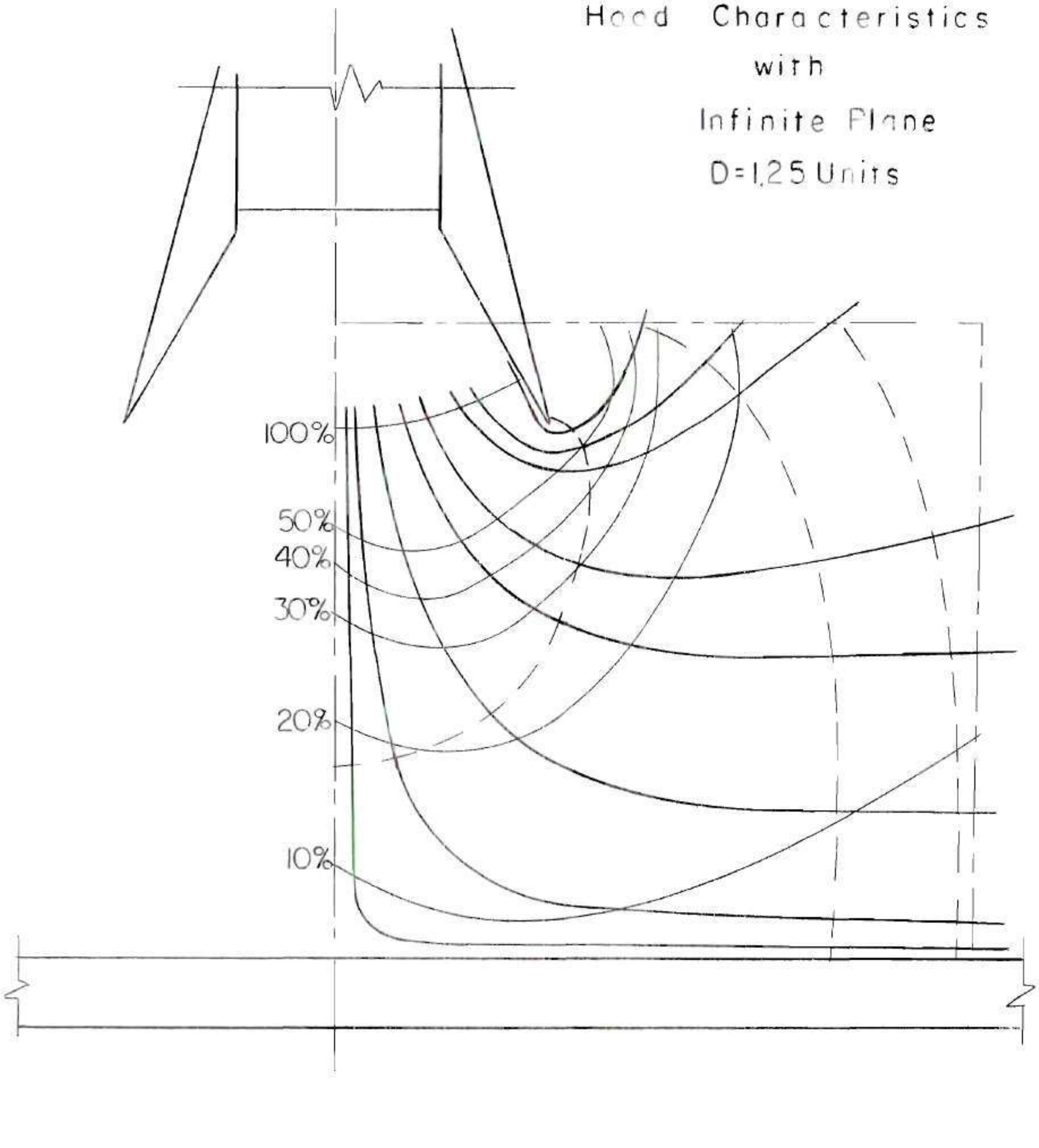

Figure 19. Map of Flow, Series 2c

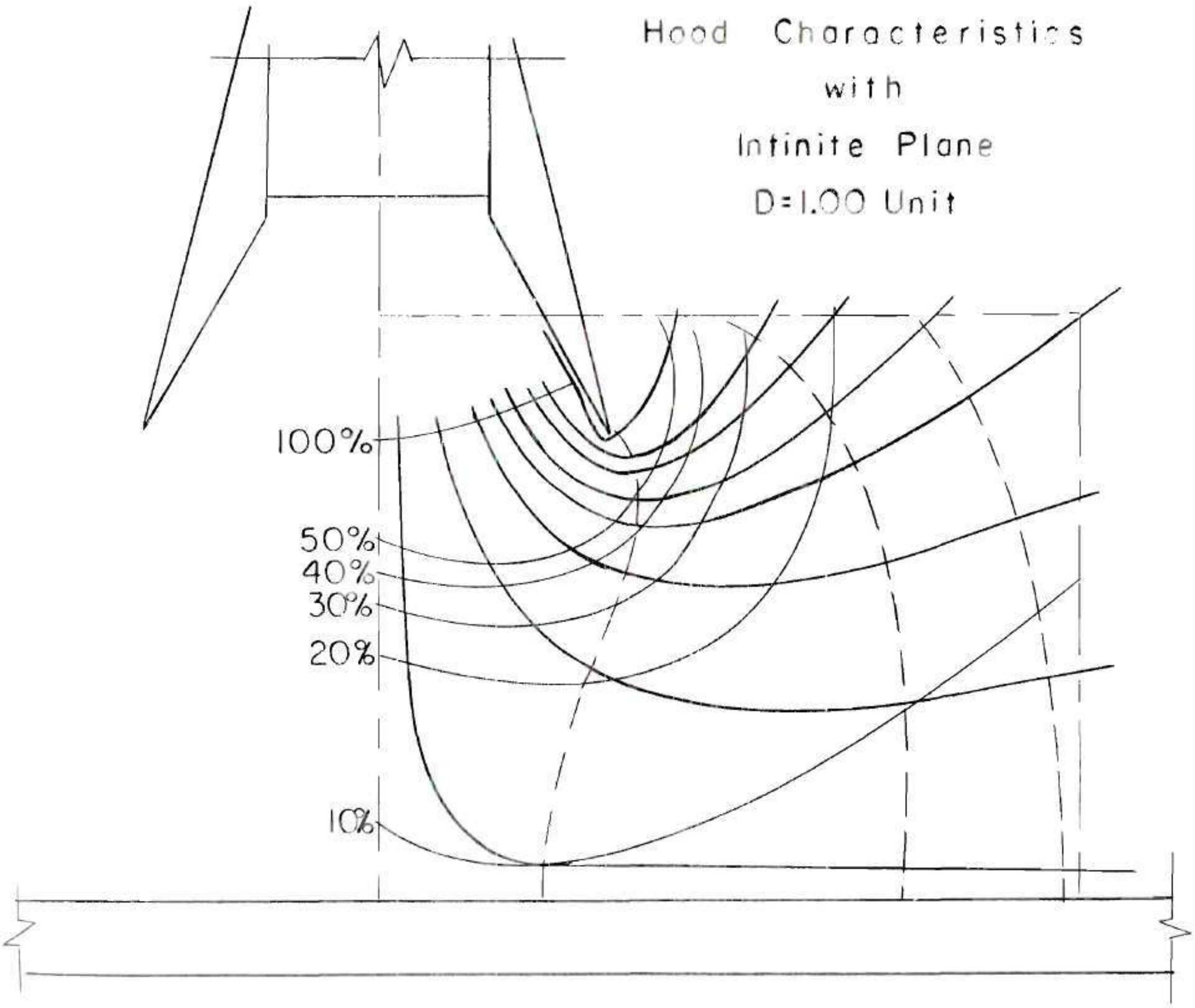

Figure 20. Map of Flow, Series 2d

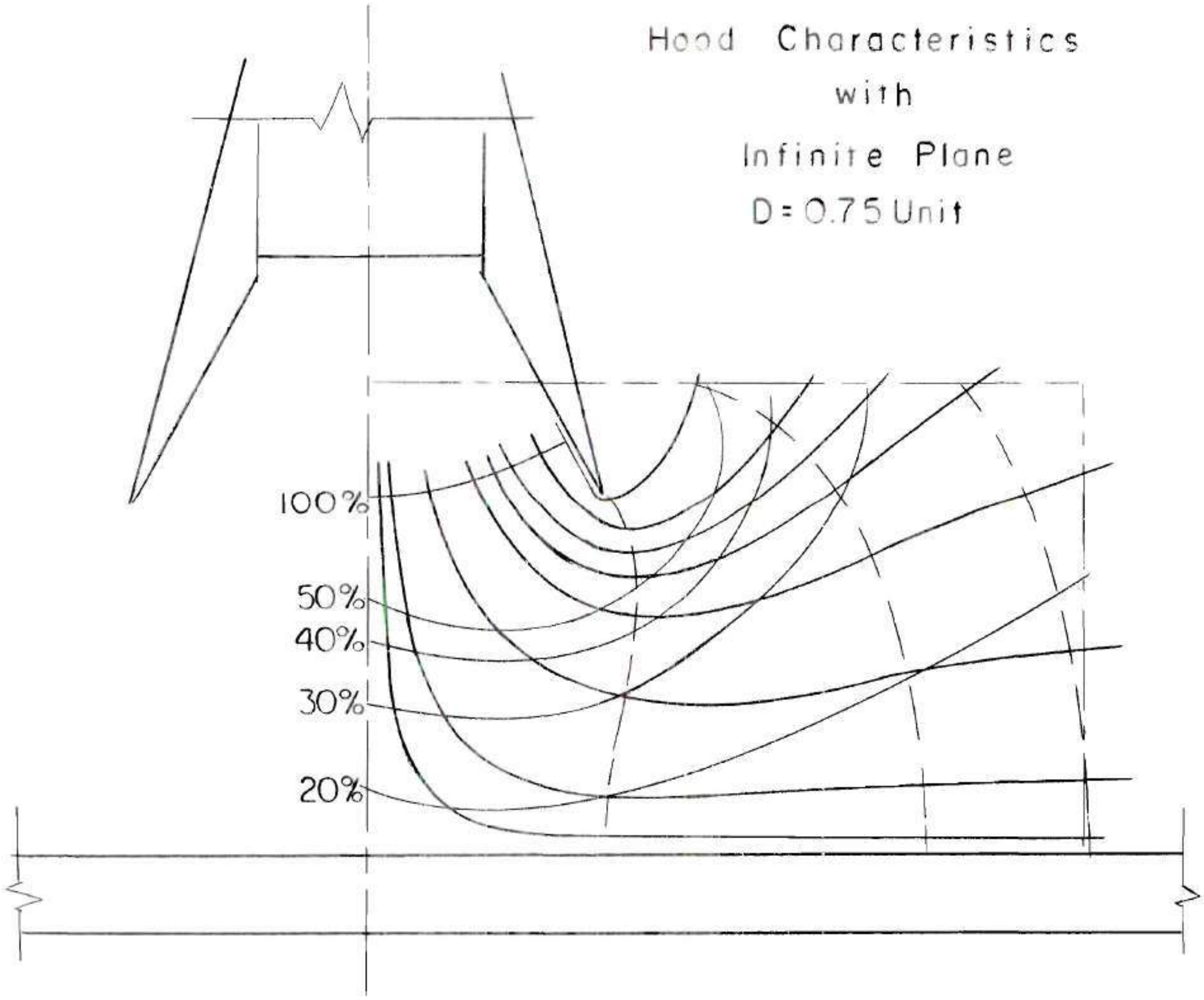

Figure 21. Map of Flow, Series 2e

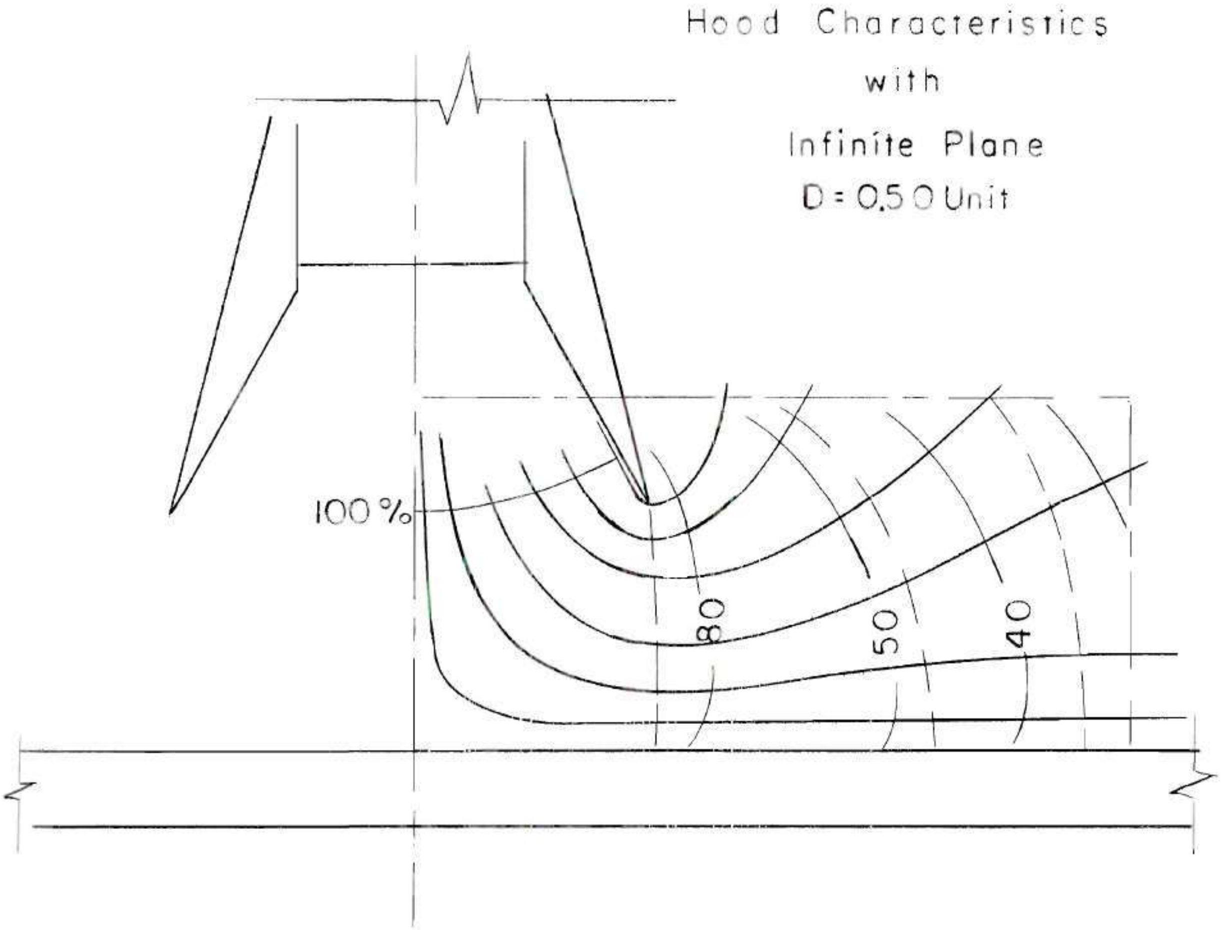

Figure 22. Map of Flow, Series 2f

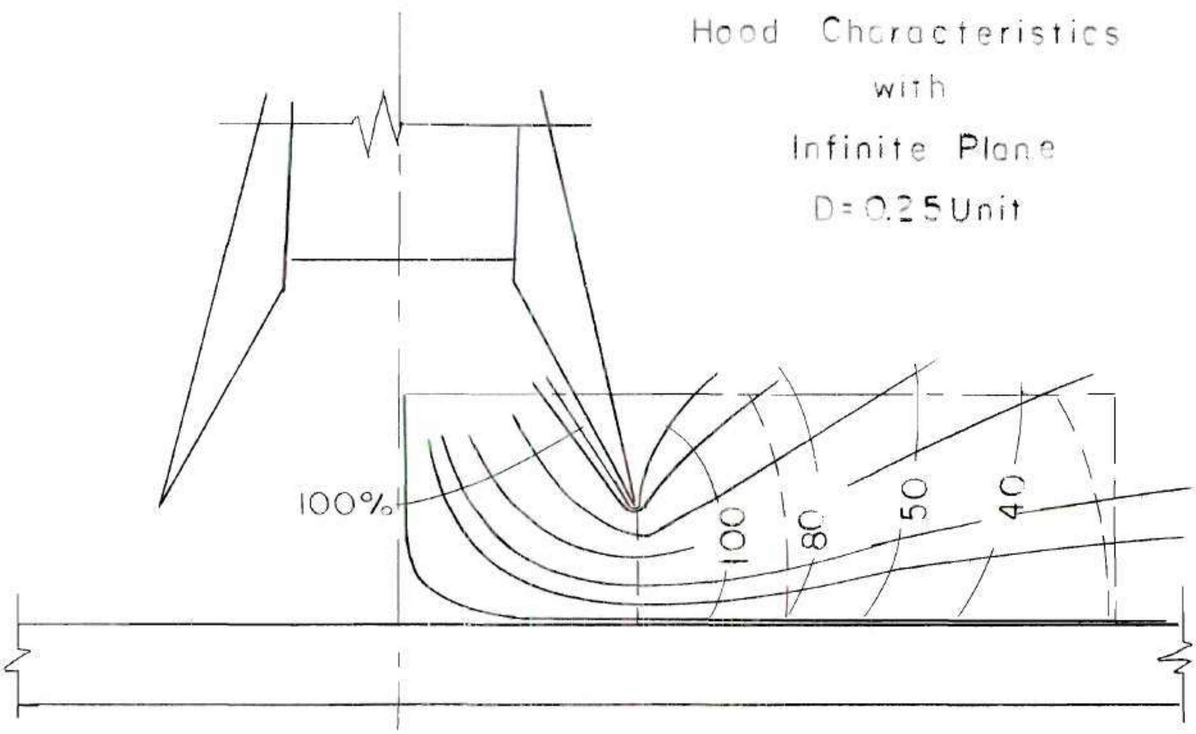

Figure 23. Map of Flow, Series 2g

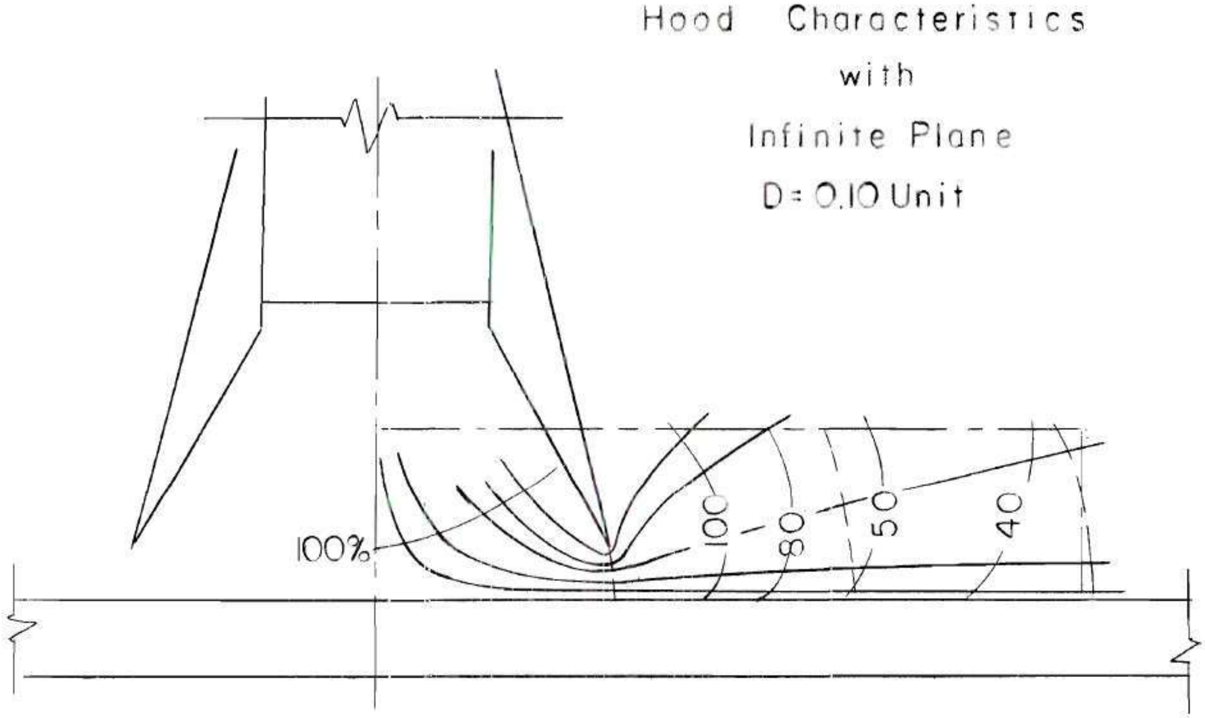

Figure 2.4. Map of Flow, Series 2h

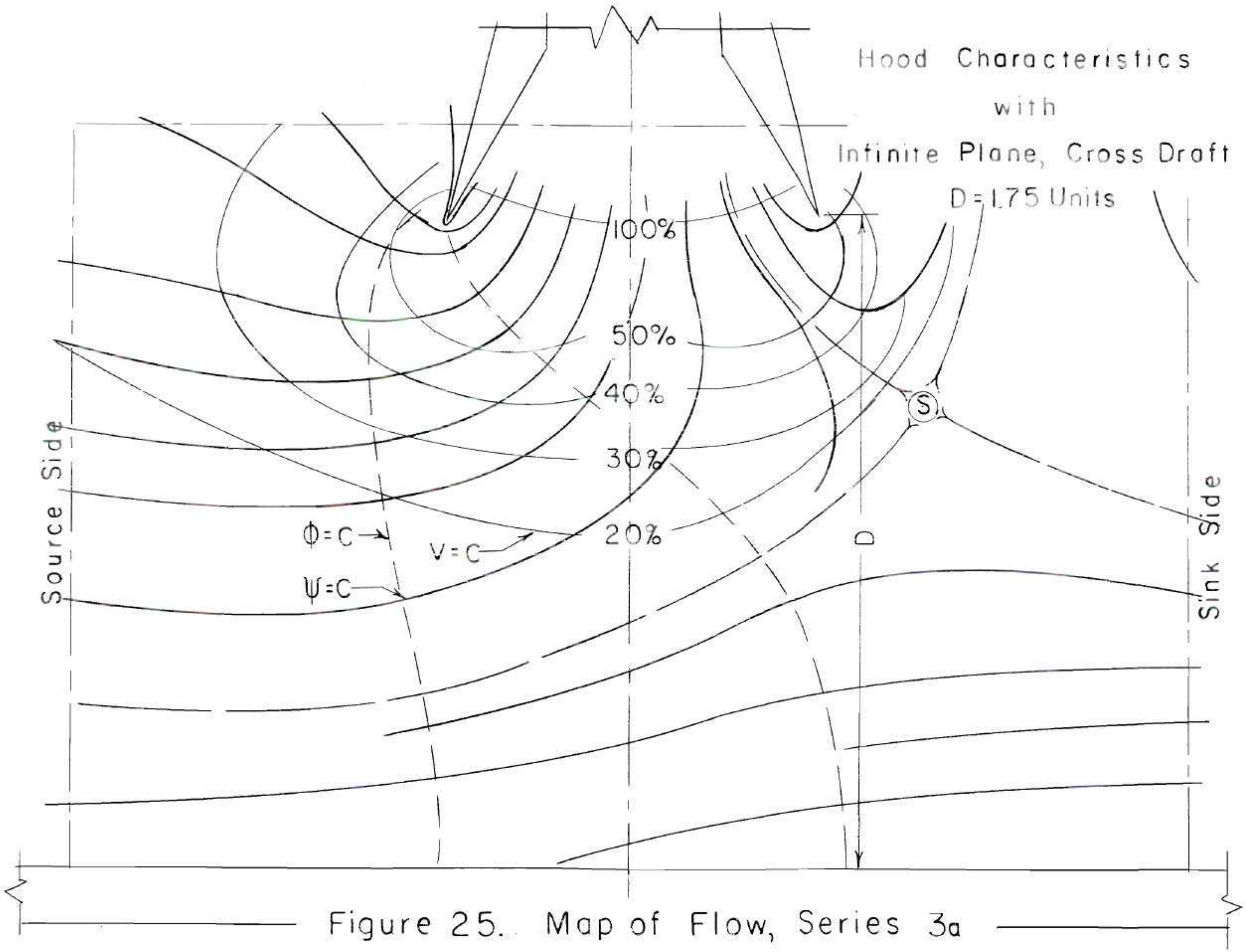

Figure 25. Map of Flow, Series 3a

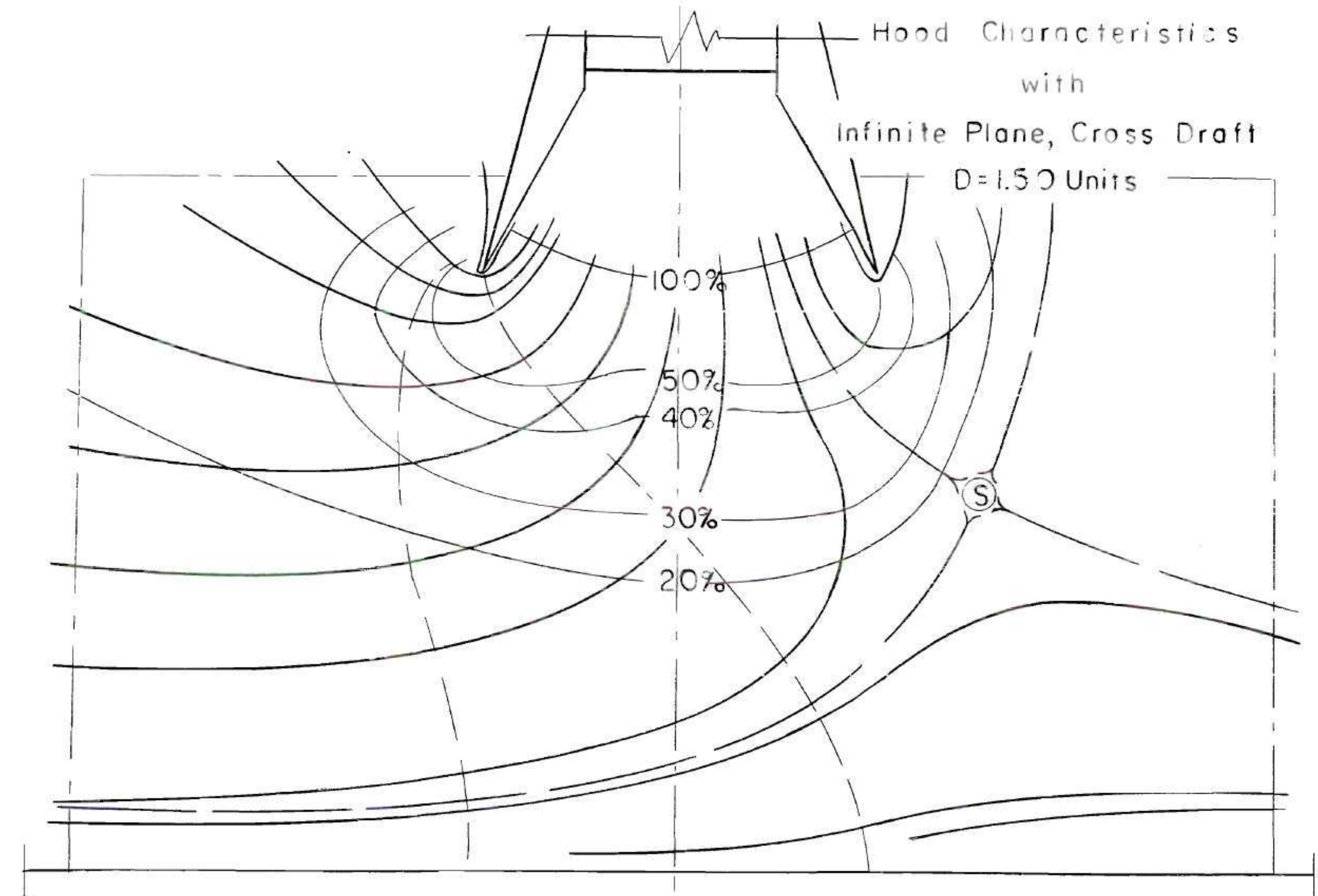

Figure 26. Map of Flow, Series 3b

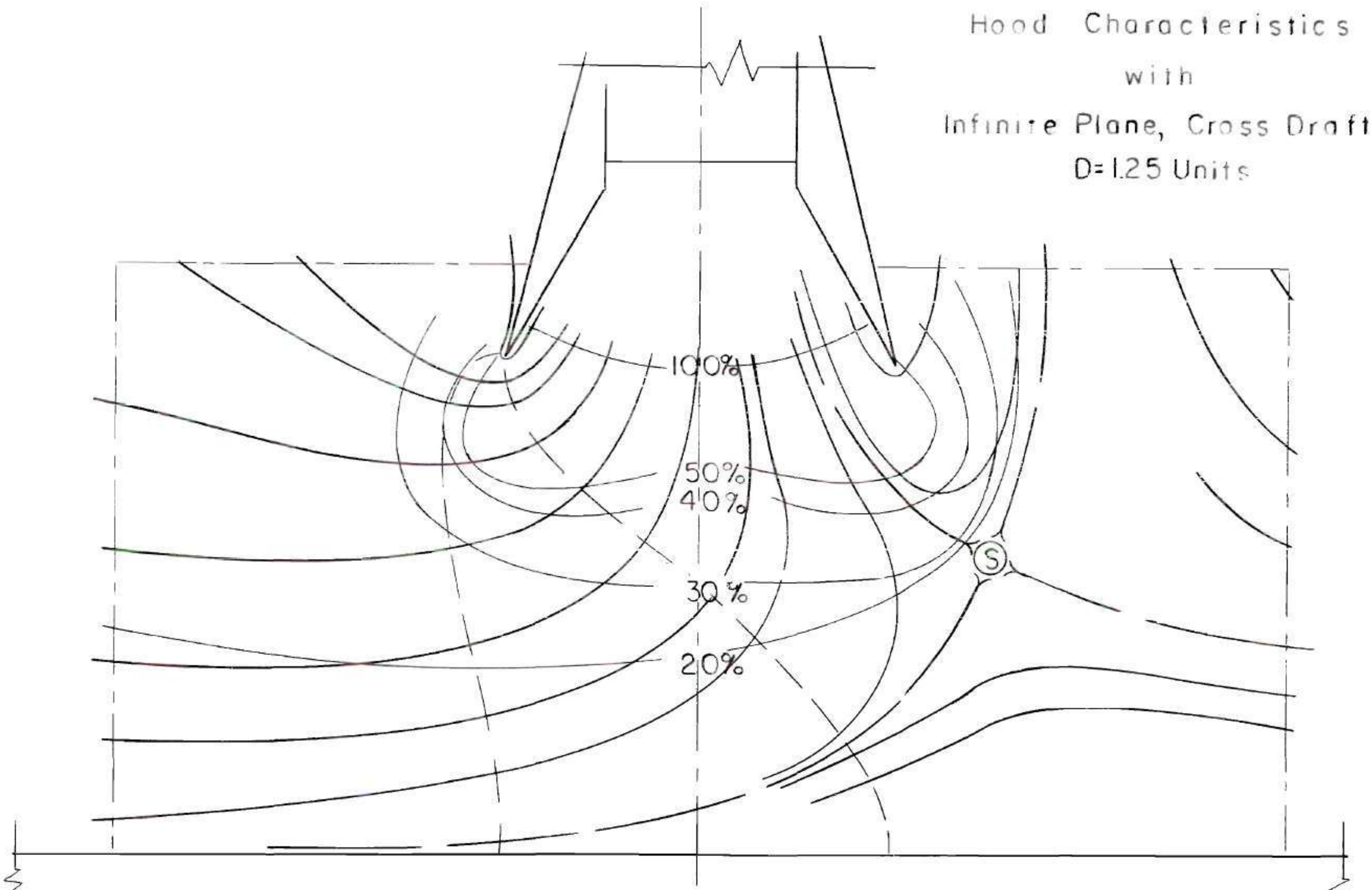

Figure 27. Map of Flow, Series 3c

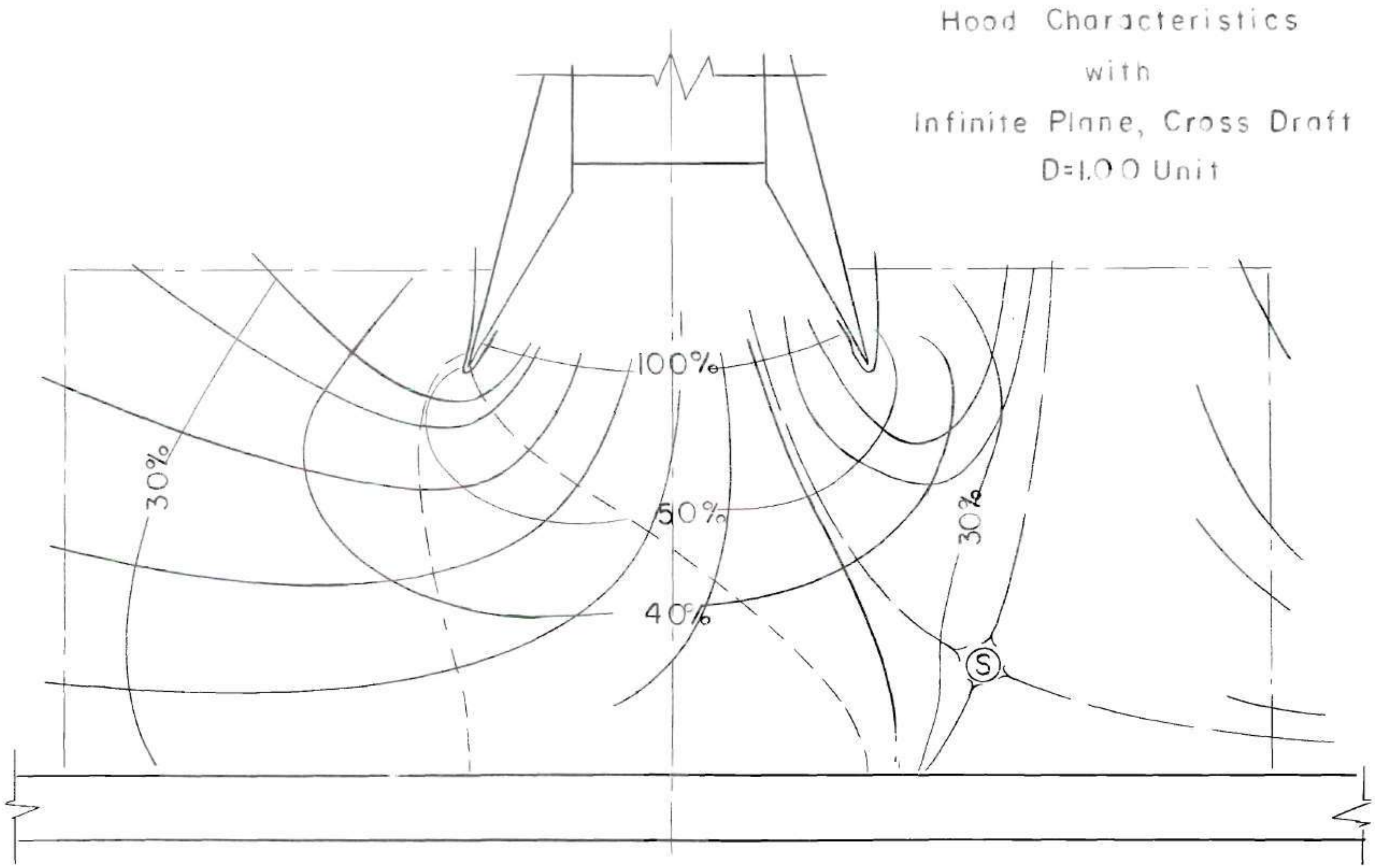

Figure 28. Map of Flow, Series 3d

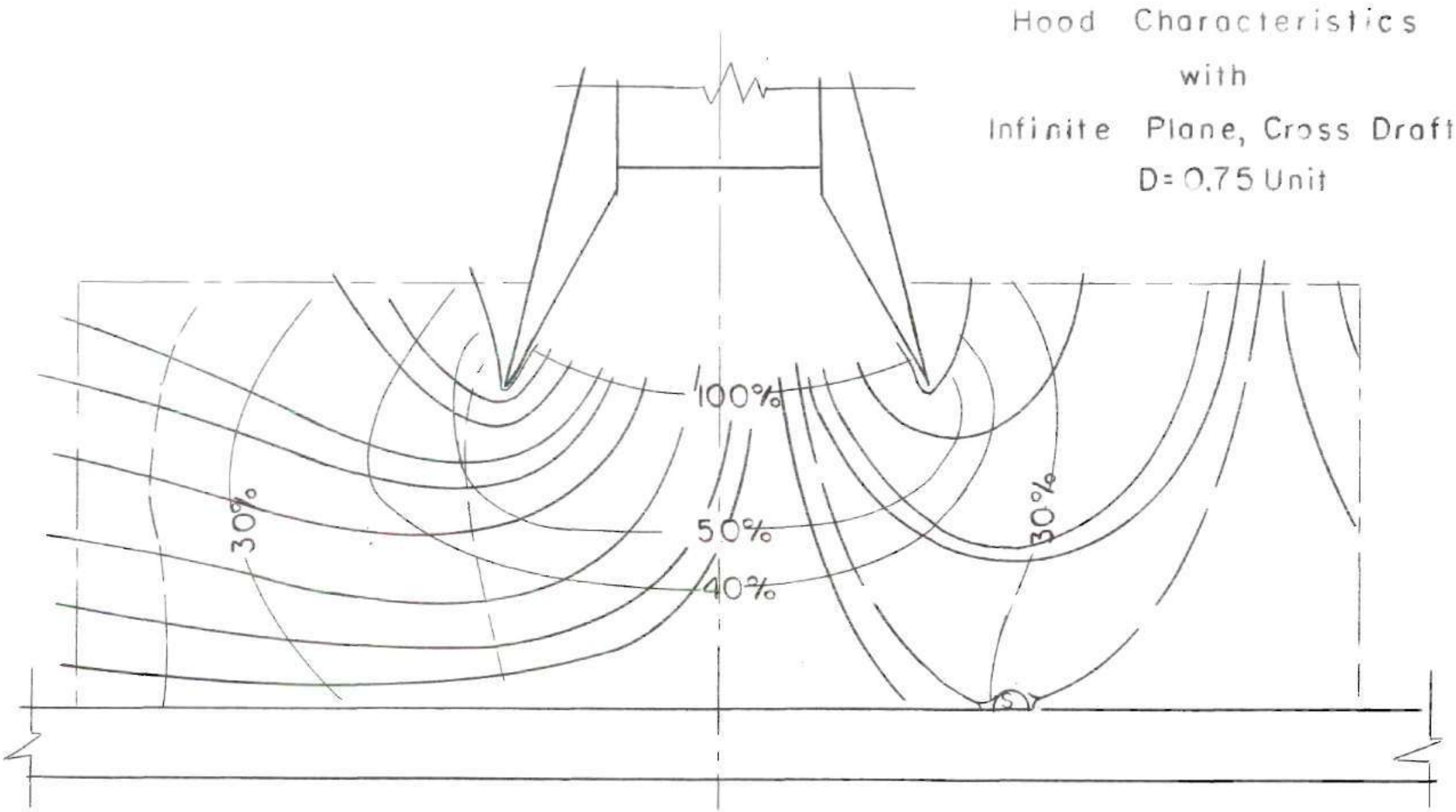

Figure 29. Map of Flow, Series 3e

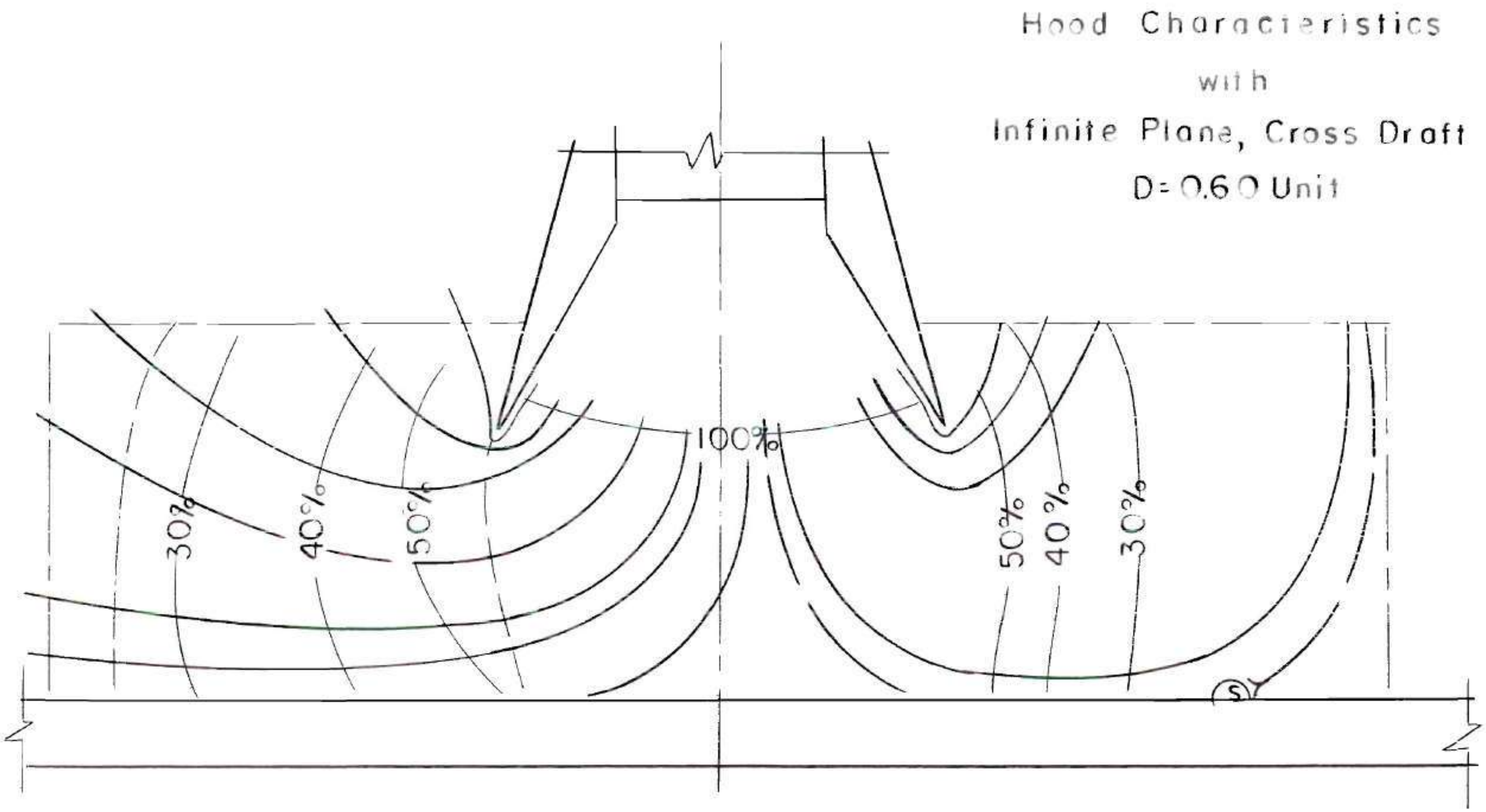

Figure 30 Map of Flow, Series 3f

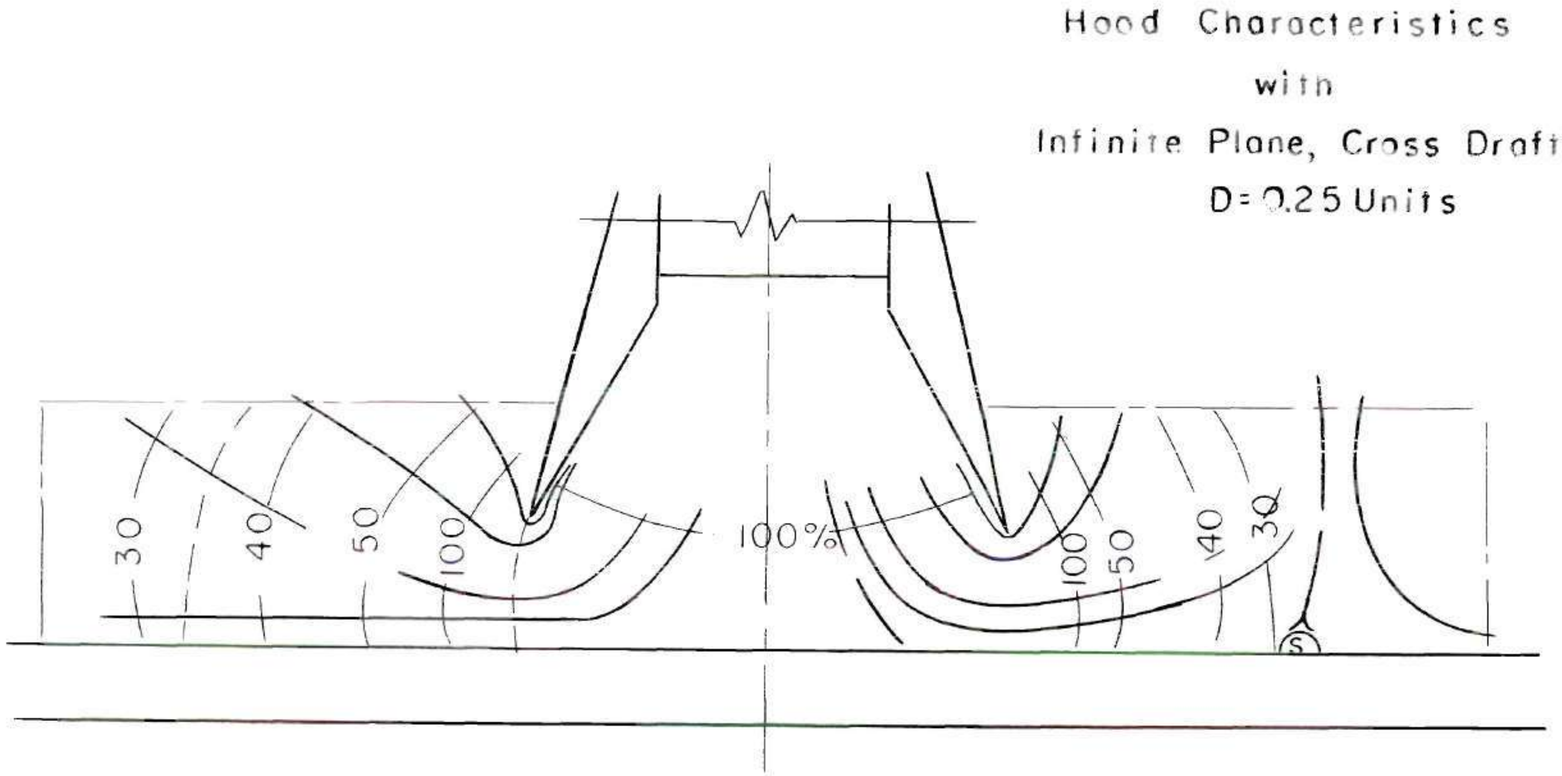

Figure 31. Map of Flow, Series 3g

Hood Characteristics
with
Infinite Plane, Cross Draft
D = 0.10 Unit

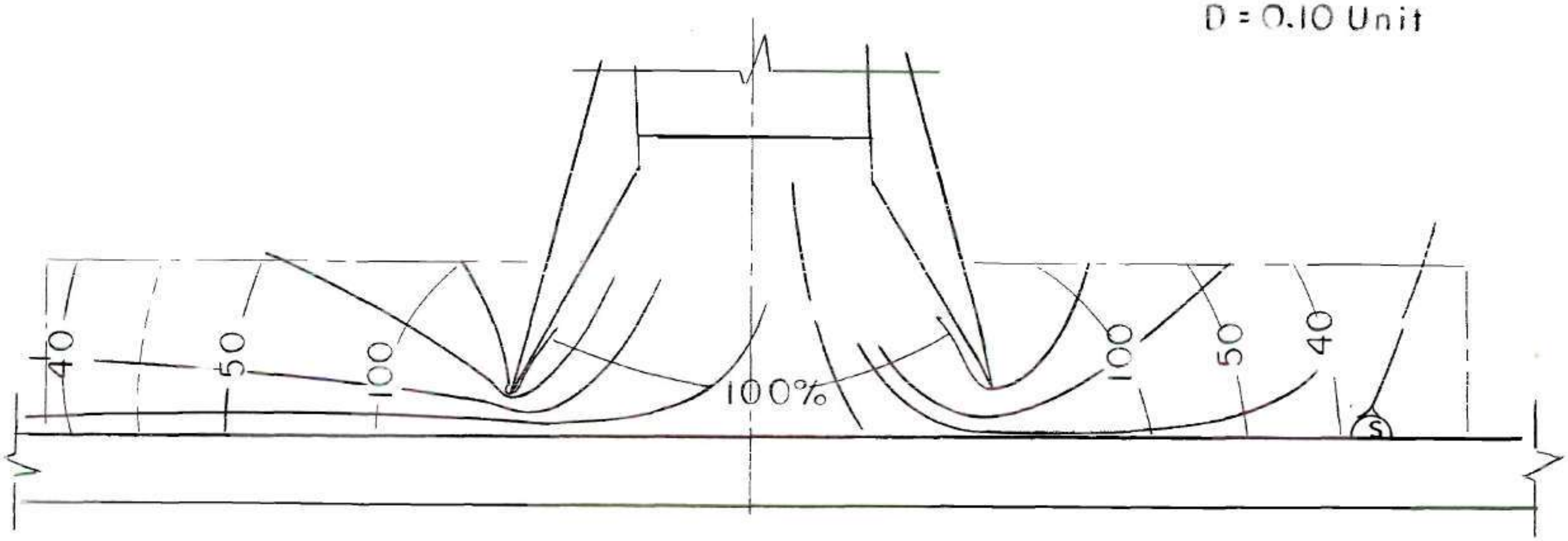

Figure 32. Map of Flow, Series 3h

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